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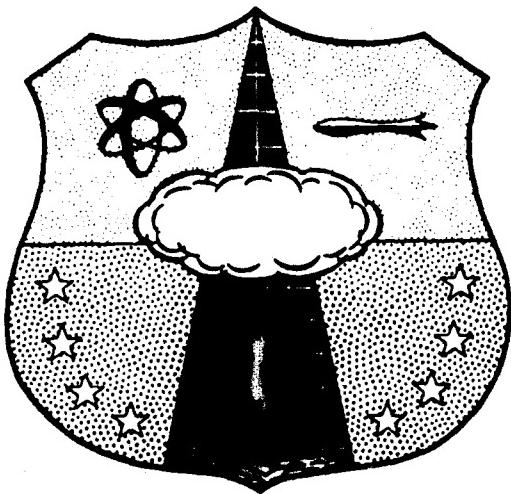
A SUMMARY OF RECENT REPORTS PRODUCED UNDER
AFSC PROJECT 1080

NUCLEAR WEAPONS EFFECTS ON HARDENED STRUCTURES

Compiled by

JOHN E. SCOTT
Captain   USAF

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September 1961

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NUCLEAR WEAPONS EFFECTS ON HARDENED STRUCTURES

Compiled by

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Captain   USAF

September 1961

Research Directorate
AIR FORCE SPECIAL WEAPONS CENTER
Air Force Systems Command
Kirtland Air Force Base
New Mexico

Approved:

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Project No. 1080

ABSTRACT

This document presents abstracts or summaries of all AFSWC Technical Reports, Notes, and Manuals published under Project 1080, "Nuclear Weapons Effects on Hardened Structures."

Some editing and paraphrasing of certain classified paragraphs within this report have been done in order that it may be published as UNCLASSIFIED.

This document supplements AFSWC-TN-59-11, A Summary of Reports Produced under ARDC Project 1080, "Protective Construction and Target Vulnerability" and its predecessors, which relates more fully the effort performed prior to the project's transfer to AFSWC.

PUBLICATION REVIEW

This report has been reviewed and is approved.
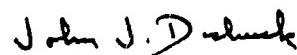
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The Air Force Shock Tube Laboratory

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AFSWC-TR-61-47   Unclassified Report
University of Illinois   Contract AF 29(601)-2372

THE INVESTIGATION OF DEEP REINFORCED CONCRETE BEAMS
UNDER STATIC AND DYNAMIC LOADING

VOL. I. The object of this investigation was to study the strength and behavior
in flexure of simply supported deep reinforced concrete beams subjected to
slowly and rapidly applied loads, as a basis for the development of rational
and efficient design procedures. In particular, it was desired to determine
the behavior in flexure under dynamic load and to compare it with the static
behavior; to determine the relation of the ultimate deflection under dynamic
load to the ultimate static deflection; to determine the increase in flexural
strength as a function of strain rate or some other factor; and, if the data
collected were sufficient, to recommend design procedures for deep reinforced
concrete beams.

VOL. II. The object of this investigation was to determine the strength and
behavior in shear of reinforced concrete deep beams subjected to static and
dynamic loading, to determine whether the dynamic mode of failure is different
from the static mode of failure, and to evaluate the effectiveness of web re-
inforcement.

AFSWC-TR-61-36   Confidential Report
University of Illinois   Contract AF 29(601)-2390

THE AIR FORCE DESIGN MANUAL: DESIGN OF PROTECTIVE
STRUCTURES TO RESIST THE EFFECTS OF NUCLEAR WEAPONS

This is the second draft of the Air Force Design Manual. Its intended use
will be for planning and designing structures to resist the effects of nuclear
weapons ranging into the megaton class. The emphasis is primarily on under-
ground construction. The material presented is derived from existing knowledge
and theory, so that the manual is also a report of the state of the art.

Starting with general considerations of site selection and structural function,
various phases of design are considered; free-field phenomena in air and ground,
material properties, failure criteria, architectural and mechanical features,
radiation effects, surface openings, conversion of free-field phenomena to loads
on structures, and the design and proportioning of structural elements and
structures.

The appendixes include a treatment of dynamic theory of structures, illus-
trative design problems, and a list of nomenclature.

AFSWC-TR-61-32   Unclassified Report
Armour Research Foundation   Contract AF 29(601)-2652

STATIC EXPERIMENTS FOR THE STUDY OF THE INTERACTION
OF BURIED STRUCTURES WITH GROUND WAVES

An experimental program was conducted to evaluate and extend some of the basic assumptions and concepts which were used in the soil-structure inter-action theory developed by Armour Research Foundation. These experiments were limited to static experiments and examined the form of the arching force which acts on buried cylinders which are axially loaded.

Compacted Ottawa sand was used for these experiments. The uniaxial compressive loading characteristics of this soil were observed to be almost linear on the loading part of the cycle. However, when unloaded the material exhibits some hysteresis characteristics. Experiments were performed on a number of buried models which varied in length and stiffness. The soil mass was loaded pneumatically to 20 psi. These experiments indicated that, for the loading part of the cycle, the assumed form of the arching force was very good. The hysteresis characteristics of the soil require that some modifications of the concept be made.

Auxiliary experiments were performed on small samples of soil which were confined in a steel cylinder and compressed axially. These experiments indicated that the side wall friction effects were appreciable. Further experiments with various wall treatments, such as the application of Teflon sheets, indicated that a large portion of the frictional effect could be eliminated.

AFSWC-TR-61-25   Unclassified Report
Armour Research Foundation   Contract AF 29(601)-2564

STRESS PHENOMENA IN SEMI-SOLIDS

The research conducted under this contract had four principal objectives.

a. First was determination of stress distributions on the boundaries of unlined circular, elliptical, and round-cornered square holes in large thin photoelastic plates subjected to a dynamic point load on one edge. The centers of all the holes were identically located with respect to the load point. The effect of variation in wavelength of the dynamic shock was also studied.

b. Second was a comparison of the stress distributions on the boundaries of three unlined circular holes located at constant depth below a dynamic point load applied to the edge of a large thin photoelastic plate, but at varying horizontal distances from the load point.

c. Third was a study of the stress distribution on the boundary of a lined circular hole in a large thin photoelastic plate subjected to a dynamic point load on one edge.

d. Fourth was the calibration of electrical resistance strain gages embedded in a large thin photoelastic plate subjected to a dynamic point load on one edge.

Work previously accomplished for the Air Force Special Weapons Center in the field of dynamic photoelasticity has been reported in AFSWC-TN-58-18, Investigation of Wave Propagation in Semi-Solids, and AFSWC-TR-60-4, Research Studies of Stress Waves in Earth and Model Earth Media.

During the course of the current study the use of rubber thread grids for measuring transient internal strains was refined. Later this method was supplemented by the introduction of the Moire fringe technique for determination of transient surface strains.

AFSWC-TR-61-12   Secret-FRD Report
In-House Report

SUMMARY OF FULL-SCALE FIELD TESTS OF STRUCTURES
SUBJECTED TO HIGH OVERPRESSURES

This report is a summary of blast resistant structures which received at least 20 psi overpressure when exposed to nuclear blast effects in the United States full-scale field tests. General information on the blast, the structure, and the test results have been included where available. The purpose of this report is to provide the reader with a feel for the behavior of structures exposed to nuclear blast; in addition, it is hoped that the report may provide an easy reference for those interested in the various nuclear test operations involving structures.

For those desiring more information, references have been included for each structure.

DEVELOPMENT OF A MINIATURE DYNAMIC PRESSURE GAUGE

This report describes the development of a miniature dynamic pressure gauge suitable for shock-tube use, and for use in shock flows of relatively short duration.

In the course of the program, several disk-shaped gauges, which employed a single sensor of the difference between stagnation and side-on pressure, were fabricated and tested in a shock tube. The completed gauges each contained minor modifications of a basic design, and each exhibited a different rise time, noise level, and sensitivity. Subsequently, one of these gauges, namely Q-5, was delivered to the Air Force Shock Tube Lab in December 1960 and satisfactorily passed evaluation and calibration tests in the 4-inch shock tube - in the 5-25 psi region for shock wave durations of 6-7 ms.

The report describes the operating principles and the design of these gauges, and summarizes the development program. It also presents preliminary data on a gauge of similar design, which incorporates diaphragms in the disk faces, and data on the operating characteristics of the gauge that was delivered to the Air Force.

THEORETICAL STUDY OF GROUND MOTIONS INDUCED IN

NONHOMOGENEOUS MEDIA BY NUCLEAR EXPLOSIONS

In Part 1, a numerical example is set up to provide a test of the method developed in Part 2 for the solution of the stresses and displacements in an elastic half space caused by an axially symmetric airblast loading. The compressional and shear wave velocities, relative to the speed of sound in air, are taken as $1 + z$ and 0.6, respectively, where z is the dimensionless depth. Results are shown for an arbitrary surface loading which has the general but not specific characteristics of the airblast from a nuclear surface burst. A complete description of coding procedures and the Balgol code are given in the appendixes.

In Part 2, a finite-difference numerical method of determining motions and stresses in an elastic nonhomogeneous half space caused by a time-dependent, axially symmetric, surface loading is presented for cases in which compressional wave velocity varies linearly with depth, while the shear wave

velocity is constant. The method may also be applied to layered media where the elastic parameters are constant in each layer but differ from layer to layer. The usual smearing of the compressional and distortional wave fronts in such methods is avoided by introducing a coordinate system following the front. In this characteristic system, regions of influence may be traced before the actual motion is determined.

AFSWC-TR-61-5   Secret-RD Report
American Machine & Foundry Co.   Contract AF 29(601)-2550

CLOSURES FOR HARDENED PROTECTIVE HANGARS

Methods for designing closures for hardened dome and arch aircraft shelters are described and discussed. Seven closure concepts for earth-covered arch shelters and six closure concepts for concrete dome shelters are described in detail and are compared. Sample calculations are given for predicting the response of closure structures when subjected to blast loading at the 100-psi overpressure level. Solutions to important design detail problems, which are unique to the design of hardened closures, are also given.

AFSWC-TR-60-55   Unclassified Report
United Electrodynamics Co.   Contract AF 29(601)-1944

RESEARCH STUDIES ON FREE FIELD INSTRUMENTATION

This paper is the final report on a free field stress gage currently under development for AFSWC by the United Earth Sciences Division of United Electro-Dynamics, Inc. The gage was tested under static and dynamic conditions to over 1,000 psi in a pressure tank especially designed and fabricated for this purpose. Present test results indicate that the gage reads within 10 percent of the free field stress up to somewhat beyond 200 psi. It is believed that future gages, developed along the same lines, will accurately measure free field stresses up to 1,000 psi.

An important side result was the design and fabrication of a dynamic pressure tank used in gage development and evaluation. The tank is capable of producing static and dynamic pressures of over 1,000 psi. At present dynamic pressure, rise times (time for pressure to reach 63 percent of its final valve) range from 10 to 40 milliseconds.

SURFACE EFFECTS ON BLAST LOADING

In this report the propagation of a blast wave from a nuclear explosion and the pressures occurring over ideal and real reflecting surfaces are considered. In separate sections the following subjects are discussed; the propagation of a blast wave in free air, the thermal radiation of an atomic weapon, the reflection process of a blast wave from an ideal surface, the influence of mechanical effects on the reflection of a blast wave, and the effects of atmospheric inhomogeneities on shock-wave propagation. The results are summarized in a chapter where schemes for construction of the blast waves reflected over real surfaces are presented.

It is felt that significant advances in the ability to predict the propagation and reflection of atomic blast waves has been achieved. Further work is necessary, however, before the accuracy of predictions is adequate to meet the military requirements for the prediction of target damage.

RESPONSE OF ARCHES UNDER DYNAMIC LOADS

This report is concerned with a study of the response of arches subjected to the influence of transient forces.

A numerical procedure is presented for the computation of the dynamic response of arches for both the elastic and the inelastic ranges of deformation. The procedure is applicable to arches having any shape and any distribution of mass and stiffness. The distribution of the pressure along the arch and its timewise variation may be arbitrary.

The analysis is simplified by replacing the actual arch which has an infinite number of degrees of freedom by a discrete framework consisting of a series of rigid bars, flexible joints, and concentrated point masses. For the computation of the response in the inelastic range, the cross-sectional area of the arch is considered to consist of two concentrated flange areas connected by a thin rigid web. The equations of motion of the replacement system are solved by use of a step-by-step method of numerical integration.

Computer programs are described for the analysis of two general classes of problems: (a) circular elastic arches subjected to a uniform normal pressure of arbitrary timewise variation, and (b) arches of arbitrary shape subjected to a triangular moving pressure pulse. For the latter case it is possible to evaluate the response in the inelastic range of behavior.

Numerical solutions are presented for a wide range of the parameters involved, and the effects of the various parameters are discussed.

AFSWC-TR-60-41   Unclassified Report
Broadview Research Corporation   Contract AF 29(601)-546

SHOCK CHAMBER DEVELOPMENT AND EVALUATION

The development of a test facility, in which detonation of explosives in reduced pressure ambient conditions can be used to determine blast loadings on models of protective structures from spherically expanding shock waves, is described. The facility consists of a large cylindrical vacuum vessel 10 feet in diameter and 19 feet long, equipped with a model-mounting stand, charge holder, vacuum system, access ports, and quick opening door.

The development program involved tests of reduced ambient pressure scaling in a small (5-feet diameter, 9-feet long) cylindrical vacuum vessel prior to the design of the final chamber. Work in the small (predesign test) chamber also included a study of the effects of topography on the overpressures in high strength shock waves.

Tests in both the predesign chamber and the final chamber indicate that Sachs' (reduced ambient pressure) scaling of shock strengths is valid to ambient pressures as low as 0.01 atm and shock strengths as high as 50.

A description of the operation of the shock chamber for simulating detonations both at sea level and at high altitudes is also included.

AFSWC-TR-60-21   Confidential Report
Armour Research Foundation   Contract AF 29(601)-796

INTERIOR BLAST LOADING IN HOLLOW MODEL STRUCTURES

This report summarizes the results of a series of four interior loading studies, which were conducted in the Air Force 6-foot Shock Tube. Primacord high explosive was used to generate shocks having overpressures between 5 and 30 psi and durations of about 22 millisec.

A series of hollow models with some openings in the exterior surfaces was studied to determine the value of initial and maximum pressure attained inside the model. Barium titanate pressure sensors were used to measure the inside pressures on the floor and back wall of the model, as well as on small blocks placed on the floor. The basic model was a 4 x 6 x 12 inch cubicle with openings

of either 0, 30, or 100 percent in the front, back, top, or sides. Variations in roof geometry treated include parapet walls and gable roofs, both with and without eaves. A model of a full-scale field test structure was also treated. These models were tested at angles of incidence of 0°, 145° and ± 90°. Most shots were at 0°.

It is concluded that openings located in or near the front are most effective in producing high inside pressures, while gable roof models have slightly lower inside pressures than flat roof models and neither parapet walls nor eaves affect the inside loading. There is no effect of overpressure on inside pressure ratios in the 5 to 30 psi pressure range, but impulses on the block, although difficult to measure satisfactorily, appear to increase for the roof of the block and decrease for the net horizontal load on the block, as overpressure increases, For a given opening configuration, the inside pressures decrease almost linearly as the angle between the openings and flow goes from 0° to 90°, then increases only slightly in the 90° to 180° range. The shock tube loadings compare quite well with those on a very similar 24:1 large-scale model with 18 percent openings in the front and back surfaces, at 7.0 psi.

A series of curves giving the values of initial and maximum inside pressure ratios for models with simultaneous openings in the front and back is also presented. These curves are based on data from the Orientation Program.

AFSWC-TR-60-16   Unclassified Report
University of Illinois   Contract AF 29(601)-464

ANALYSIS AND DESIGN OF DOMES, ARCHES AND SHELLS

Vol I: ELASTIC ANALYSIS OF SPHERICAL DOME

Part 1 of this report presents the numerical results of an investigation of the dynamic response of the elastic spherical shell to uniform axi-symmetric pressures. The continuous dome has been replaced by a series of elastic members having distributed flexural and membrane stiffnesses. The internal moments, thrusts, and shears for the replacement mechanism have been expressed in terms of the tangential and radial displacements of the middle surface. The time-dependent response of the dome to external pressures was investigated by solving these force-displacement relations using an iterative technique similar to physical relaxation.

The response was investigated for two types of edge restraint: (a) rigid support, and (b) moment-free support. Also studied were the effect on the response of the radius-to-thickness and period-to-pulse duration ratios. Finally, the effect of peak dynamic pressure on axi-symmetrical buckling was investigated. The results and conclusions are summarized in the text.

Part 2 of this report discusses a physical mechanism developed to represent shell action for domes dynamically loaded into the inelastic range. A sandwich type of cross section with two thick uniformly reinforced face sheets is introduced to simulate the behavior of a concrete dome.

A physical relaxation is used in the computation of the dome response, and the incremental loading procedure is described in detail. Even for symmetrical pressures, the possible combinations of elastic and plastic areas in the dome surface becomes extremely large. Thus, in an actual numerical calculation, a large amount of bookkeeping is necessary. This bookkeeping problem was solved in a unique fashion for a binary computer and is presented in the chapter devoted to the computer program.

Vol II. DYNAMIC RESPONSE OF CIRCULAR ARCHES UNDER A UNIFORM
        ALL-AROUND PRESSURE PULSE

This study is concerned with the behavior of arch structures under dynamic loads. Numerical solutions are presented for the elastic response of two-hinged circular arches of constant cross section subjected to a uniform all-around triangular pressure pulse with an initial peak. The parameters investigated include the duration of the pressure pulse, the magnitude of the peak pressure as compared to the critical buckling pressure, the geometric and physical properties of the arch, and the initial out-of-roundness of the arch.

The problem is analyzed approximately by replacing the continuous arch by a framework consisting of a series of rigid bars and flexible joints. The actual mass of the structure is lumped as a series of point masses at the joints. The equations of motion for the analogous framework are solved by use of a step-by-step method of numerical integrations.

AFSWC-TR-60-11   Secret Report
Armour Research Foundation   Contract AF 29(601)-547

COMPARATIVE PROTECTIVE STRUCTURAL DESIGN

The objective of this study was to develop cost figures for hardened structures employed in air weapons systems. The design techniques employed in the study were based on the best available methods. If these were regarded as incomplete, or insufficiently accurate as compared with design methods used elsewhere in the study, rapid and approximate methods were developed specifically for the program. This study was further directed toward determining minimum cost designs of complete protective structures for ultimate use by Air Force planning agencies in selecting the optimum combination of hardening, mobility, and dispersal for given funding levels. This required an extensive investigation of structural components. The final report contains cost figures in terms of both structural elements (beams, slabs, columns, etc.) and for structural enclosures (cubicles, large-enclosures, etc.). In addition, silos, silo doors, arches, and domes are treated in separate appendixes. The study showed that underground structures

were far less expensive than surface structures at moderately severe over-pressures. At very high pressures, surface structures are regarded as not feasible, while underground structures appeared reasonable from a cost stand-point. Optimum burial depths, which resulted from the design method assumed, were found to exist for the higher overpressures. It was found less expensive to build underground protective structures in sand than in clay.

AFSWC-TR-60-8   Unclassified Report
American Machine & Foundry Company   Contract AF 29(601)-1190

THEORETICAL STUDY OF GROUND MOTION PRODUCED
BY NUCLEAR BLASTS

This study is part of a program aimed at analytically determining free-field ground motions of soils in response to overpressure loadings caused by nuclear weapons. It is desired that the analysis will ultimately provide the designer of underground protective structures with the necessary quantitative information on ground motions and pressures as a function of soil properties and weapon yield.

A fair idea of the behavior of soil may be gained from a knowledge of less complicated media. It is, therefore, natural that the first need is a thorough understanding of elastic phenomena. Then extensions into the visco-elastic phenomena may be made.

As a first approximation to the actual problem, the two-dimensional motion of an elastic half-plane under an exponentially decaying normal load traveling at constant velocity along the boundary is determined analytically and the results are presented graphically. Analytic expressions in integral form are then ob-tained for the three-dimensional axi-symmetric motion of an initially quiescent homogeneous isotropic elastic half-space under an arbitrary axi-symmetric time-dependent normal loading. These expressions are then utilized for the special case of a concentrated normal point load and a uniform concentrated normal ring load suddenly applied and thereafter maintained at a fixed position on the plane boundary. Analytic expressions are also obtained for the three-dimensional axi-symmetric motion of a homogeneous isotropic visco-elastic half-space under identical conditions as for the elastic case.

PRELIMINARY DESIGN METHODS FOR UNDERGROUND
PROTECTIVE STRUCTURES

This contract had as its objective the determination of simplified methods and criteria for the design of underground structures subjected to nuclear blast loading.

Available data were investigated, classified and studied. Required analytical studies were made where needed, to supplement the presently available data. Design methods and procedures for simplified application of the limited available knowledge were developed to the extent that they are suitable for use in preliminary design.

Recommendations for future study are made. Because of the lack of data and knowledge, many areas in this volume were cursorily treated, and will be studied more thoroughly in the next year's effort.

RESEARCH STUDIES OF STRESS WAVES IN
EARTH AND MODEL EARTH MEDIA

A solution to the problem of the stress distribution on the boundary of a circular hole in a large plate during passage of a stress wave of long duration is presented. The solution was experimentally obtained by using a low modulus model material in a combined photoelasticity and grid analysis. The results of the investigation indicate that a biaxial state of stress exists, such that the maximum tensile stress, produced in the free field, was approximately 0.45 times the maximum compressive stress. The study also indicates that the maximum compressive stress on the hole boundary can be computed with a fair degree of accuracy by applying the Kirsch solution for a hole in an infinite plate and considering the free field biaxial stress conditions. The maximum tensile stresses on the hole boundary were always found to be smaller than the predicted values. As far as the author knows, no solution has ever been published in the technical literature for an impact-produced time dependent stress distribution around a discontinuity.

A laboratory program was conducted to study the performance of small diaphragm and of barium titanate pressure gages. Barium titanate gages embedded in cylinders of clay and cylinders of urethane rubber were subjected to dynamic loadings, while the diaphragm gages, embedded in urethane rubber cylinders, were subjected to static and dynamic loadings. The embedded barium titanate gage response was in all instances approximately 40 percent greater than the response for an equivalent air shock loading. The embedded diaphragm gage response to dynamic loadings was approximately 80 percent higher than the response for an equivalent static air pressure loading and about 30 percent higher than the static response of the embedded gage. The percent increased in response depends upon the gage type and the material properties of the medium in which it is embedded. It was also established in the program that embedded gages respond only to the normal component of stress acting on their sensitive faces. The closely controlled performance of these gages in materials whose properties are very accurately known is expected to provide many answers to the rather nebulous problem of making underground measurements in soils loaded by nuclear detonations. Some preliminary development of a wafer-thin sensing element which has the same response to static and dynamic loadings when embedded is discussed.

An attempt was made to obtain the stress distribution on the boundary of an embedded rigid obstruction in a large plate during passage of compressive stress waves. A combined photoelasticity and grid analysis was used. The results of the program indicate that the maximum shearing stresses can be obtained from the photoelasticity data with sufficient degree of accuracy. However, in order to separate the principal stresses and determine the normal, tangential, and shear components of stress on the boundary of the obstruction, data from a grid analysis are required. The results of the program indicate that the grid method should be further developed to obtain these data.

AFSWC-TR-60-3   Secret Report
Armour Research Foundation   Contract AF 29(601)-1169

CONCEPTS OF PRELIMINARY DESIGN OF STRUCTURE PROJECTS
FOR UNDERGROUND NUCLEAR DETONATIONS

This report describes a structure test program for contained underground
nuclear detonation, designed to obtain data which do not exist at the present
time and which would give designers additional guidance needed in planning
protection in relatively high pressure fields. Four individual tests are proposed,
all at the same free-field stress condition, and each is designed to answer at
least one specific question regarding the interaction of a buried structure with
a ground shock wave. A cost estimate is also given.

AFSWC-TR-60-3 Appendix A   Secret Report
Armour Research Foundation   Contract AF 29(601)-1169

FREE-FIELD PREDICTIONS OF CONCEPTS OF PRELIMINARY
DESIGN OF STRUCTURE PROJECTS FOR
UNDERGROUND NUCLEAR DETONATIONS

This appendix describes a method which furnishes estimates of the earth
motions, stresses, strains, etc., resulting from a contained underground
nuclear detonation. This appendix also attempts to delineate those factors which
are influential in controlling the shock or stress waves which propagate outward
from the epicenter, and to give specific estimates of earth motions in the white
and reddish tuffs found at the Nevada Test Site for an approximate range of
stress levels from 400 to 2,000 psi. In addition, a factor is given which permits
crude estimates of the earth motion to be made in other soil or rock.

AFSWC TR-60-3 Appendix B   Secret Report
Armour Research Foundation   Contract AF 29(601)-1169

THE INTERACTION OF BURIED STRUCTURES WITH GROUND SHOCK OF
CONCEPTS OF PRELIMINARY DESIGN OF STRUCTURE PROJECTS FOR
UNDERGROUND NUCLEAR DETONATIONS

This appendix presents a theory or concept which can be used to estimate
the forces acting on a buried structure when the structure is subjected to a
ground shock wave. This work is intended to be applicable primarily for the
type of rock found at the Nevada Test Site, such as white or reddish tuff.

A discussion of the free-field variables is given, together with an idealization of the stress wave forms of interest. The basis of the soil-structure interaction concept lies in the assumption of the nature of the forces acting on the buried structure. The force acting on the structure is assumed to be composed of two parts.

One, the wave force, is due to the sudden motion of the surrounding media and the subsequent state of stress in the ground shock wave. The other, the arching force, is due to the local deformation or displacement of the structure relative to the surrounding media. The motion of the structure is governed by the usual equation of motion; however, in this treatment the forcing term has been split into two uncoupled terms. The wave force term is a function of the relative displacement between the structure surface and its corresponding soil position.

The response of the buried structure is given for a range of ground shock waves parameters, structure configurations, and structure parameters, and includes some analysis of shock isolation systems.

AFSWC-TR-60-1   Confidential Report
University of Michigan   Contract AF 29(601)-467

DOORS AND ACCESS OPENINGS TO PROTECTIVE STRUCTURES

The general objective of this study was to develop analytical methods which may ultimately be applied to the design of access openings to protective structures. Doors for dome, arch, rectangular, and silo-type structures are considered from an intuitive point of view. Because of the mathematical difficulties involved, it is proposed that the continuous structure (both the main shelter and the door) be replaced by an equivalent frame for the analytical investigation. A method for analyzing the dynamic elasto-plastic response of the frame is presented.

AFSWC-TR-59-72   Unclassified Report
University of Illinois   Contract AF 29(601)-468

BEHAVIOR AND DESIGN OF DEEP STRUCTURAL MEMBERS (in 7 volumes)

The purpose of this investigation was to obtain information on the strength and behavior of deep beams and slabs of either reinforced concrete or steel under static and high-energy impulsive loadings, and to develop means for the prediction of this behavior.

Part 1.   BEHAVIOR AND DESIGN OF DEEP STRUCTURAL MEMBERS

The report has been issued in seven parts of which this is Part 1. This part contains a summary of each of the specific investigations which are reported in detail in Parts 2-7. The summaries include the object and scope of the test programs, and digests of the test results and conclusions for each part.

Part 2.   TESTS OF REINFORCED CONCRETE DEEP BEAMS WITH WEB AND COMPRESSION REINFORCEMENT

The results of tests of seven reinforced concrete deep beams with tensile and web reinforcement and two beams with tensile and compressive reinforcement are described in this report. Several patterns of web reinforcement were used. The beams with web reinforcement had a span-depth ratio of about 3.0 and the beams with compressive reinforcement had a span-depth ratio of 2.32. All beams were tested under uniform, slowly applied loading. The general behavior of the test specimens is described and explanations of the observed phenomena are given.

Part 3.   TESTS OF REINFORCED CONCRETE DEEP BEAMS

Tests of eleven reinforced concrete deep beams subjected to slowly applied, uniform loading are described in this report. Studies of the strength and behavior of simply supported, reinforced concrete deep beams are made, and procedures for the prediction of the static load-deflection behavior of such members up to flexural failure are presented.

Part 4.   DYNAMIC TESTS OF REINFORCED CONCRETE DEEP BEAMS

Tests of simply supported reinforced concrete deep beams subjected to rapidly applied loads are described in this report. Five beams were tested under a triangular-shaped pulse and three beams were tested under a flat-top pulse of "infinite duration." Five beams were tested statically to serve as control beams for the beams tested dynamically. Studies of the relationships of the sum of the measured reactions to deflections, steel strains, and concrete strains are made. Data concerning the effect of strain rate on the behavior are presented.

Part 5.   RESISTANCE AND BEHAVIOR OF REINFORCED CONCRETE BEAMS OF NORMAL PROPORTIONS UNDER RAPID LOADING

The object of this investigation was to obtain information on the strength and behavior of reinforced concrete beams subjected to rapid loading. To this end, 33 beams of various strengths, 6 by 12 inches in cross section and 9 feet or 12 feet-8 inches in span, were tested under static and dynamic loads. Three percentages of tension reinforcement were employed using intermediate grade steel. Some beams also had compression and/or shear reinforcement. Concrete strength, beam width and depth, and yield strength of reinforcement were essentially constant.

Eight of the two-point loaded beams were tested statically, requiring from about 2 to 6 minutes each to reach collapse deflection. In the dynamic tests of the other 25 beams, loads were applied in from 0.1 to 0.8 times the natural period of vibration of the beam. Some of the dynamic loads were of "infinite"

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duration, while others were terminated at from one-half to three times the beam period. The load levels varied from less than static yield capacity to more than dynamic ultimate capacity.

The analysis of the test results consists of determining the dynamic resistance characteristics of the test beams. This was accomplished by considering the beam to be a single-degree-of-freedom system and analyzing its behavior on an analog computer. The measured load pulse was fed into the computer along with an arbitrary resistance function for the beam. This resistance function was then changed until its response matched the response measured in the test. Dynamic resistance functions were also determined using the strain rates measured in some of the tests together with the available results of dynamic tests of coupons of reinforcing bars. The resistance functions determined with the analog computer are compared with the computed functions and with the static load-deflection characteristics. An analytical procedure for the determination of the dynamic resistance of reinforced concrete beams is proposed which involves the use of the deflection rate of yield.

The most important conclusions concern the direct relation between the dynamic yield level of a reinforced concrete beam and the yield strength of the tension reinforcement under dynamic loading; the apparently small effect that dynamic loading has on the collapse deflection of reinforced concrete beam; and the feasibility of using established formulas, developed in connection with static tests, for the prediction of dynamic resistance provided proper account is taken of the increase in yield strength of the reinforcing steel.

Part 6. THE YIELD STRENGTH OF INTERMEDIATE GRADE REINFORCING BARS UNDER RAPID LOADING

The object of this investigation was to determine the influence of rapid loading on the yield strength of deformed reinforcing bars of intermediate grade steel. Thirty-four specimens consisting of 2-foot coupons cut from No. 6, No. 7, and No. 9 bars were tested at room temperature under uniaxial tension. The static yield strengths ranged between 40,500 psi and 48,900 psi. The dynamic yield strength varied from 102 to 149 percent of the static yield strength and was related to the strain rate during yielding. Load and strain data for each bar tested is presented in graphical and tabular form.

Part 7. PLASTIC BEHAVIOR OF DEEP STEEL BEAMS INCLUDING SHEAR EFFECT

The static resistance-deformation relationship of steel I or WF beams subjected to a uniform loading that results in inelastic shear and flexural deformations is investigated. Essentially, three specimens from as-rolled 8 WF 35 beams were tested; the flanges of the beams were milled in order to obtain the desired variations in resistance. Plastic shear deformations occurred in all specimens. One specimen deformed primarily in flexure; another specimen deformed from a combination of shear and flexure. Material properties in both tension and torsion were determined from coupon data. Comparing the experimental results from the specimen tests and the torsional properties of the material, it is determined that a considerable portion of the shear resistance is derived from the flanges. A shear-moment interaction relationship is derived which defines the perfectly plastic condition. This relationship includes

a consideration of the shear distribution in the flange and an effective width of the flange in resisting shear. It is shown that the shear capacity is dependent on the shear-moment ratio of the section, although reasonably accurate shear deformations can be computed for the specimens of this investigation from a single shear-shear strain relationship which approximates the shear-shear strain relationship for no moment.

AFSWC-TR-59-71   Secret-RD Report
Stanford Research Institute   Contract AF 29(601)-542

GROUND MOTION PRODUCED BY ABOVEGROUND
NUCLEAR EXPLOSIONS

This report summarizes free-field ground motion observations made on aboveground nuclear and applicable HE detonations. Prediction methods are presented for estimation of the variation of maximum values of ground motion parameters with weapon yield and ground range.

The question of scaling cannot be resolved solely by experimental data, and for weapons detonated in Nevada the scatter of data are sufficient to mask the relationships between ground motion and known soil property variation. Geology of Eniwetok Proving Ground is grossly different from that of Nevada, and hence the ground motion at the same overpressure is within an entirely different theoretical and experimental regime than in Nevada. This makes correlation of these ground motion data with soil properties tenuous.

However, theoretical analysis of viscoelastic media and correlation of maximum values of surface particle velocity, strain, and displacement data with elastic theory suggest that transient nuclear ground motion data (with the exception of acceleration) can be treated on the basis of a "nearly elastic" medium in overpressure regions less than approximately 500 psi. A nearly elastic medium is one in which elastic parameters play a major role, while viscous and plastic parameters play minor roles. In contrast, ground motion produced by HE detonations of less than 2,560 pounds (the largest HE ground motion experiment) is strongly influenced by dissipative phenomena, and data suggest two-dimensional phenomena. Until a more complete theoretical description of the phenomena is available, these data do not provide quantitative extrapolations to nuclear detonations.

Ground motion data have been analyzed for 14 United States' nuclear experiments at Nevada Test Site, 8 United States' experiments at Eniwetok Proving Ground, and 3 United Kingdom experiments at Maralinga, Australia. Correlations are presented for horizontal and vertical acceleration and particle velocity near the ground surface and for the attenuation of acceleration and particle velocity with depth in the superseismic and outrunning regions. For the superseismic region the vertical surface displacement, stress, and strain are given. Rules of thumb are presented for the attenuation with depth of horizontal velocity and displacement.

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AFSWC-TR-59-70   Confidential Report
University of Illinois   Contract AF 29(601)-1162

AIR FORCE DESIGN MANUAL:

DESIGN OF PROTECTIVE STRUCTURES TO RESIST
THE BLAST EFFECTS OF NUCLEAR WEAPONS

This is the first draft of the Air Force Design Manual. Its intended use
will be for planning and designing structures to resist the effects of nuclear
weapons ranging into the Megaton class. The emphasis is primarily on under-
ground construction. The material presented is derived from existing knowledge
and theory, so that the manual is also a report of the state of the art.

Starting with general considerations of site selection and structural function,
various phases of design are considered: free-field phenomena in air and ground,
material properties, failure criteria, architectural and mechanical features,
radiation effects, surface openings, conversion of free field phenomena to loads
on structures, and the design and proportioning of structural elements and
structures.

The appendixes include a treatment of dynamic theory of structures, a
discussion of a solution for attenuation of stress in earth caused by three-
dimensional dispersion, and illustrative design problems. This effort is being
continued under Contract AF 29(601)-2390 and will result in publication of the
second draft of the manual.

AFSWC-TR-59-58   Unclassified Report
University of Michigan   Contract AF 29(601)-467

A DOOR DESIGN FOR TUNNEL CLOSURE

Some of the problems confronting the designer of deep underground military
installation are discussed in the preface. It is shown that placing a door near
the entrance of the tunnel leading to the heart of the installation should be con-
sidered, especially in the high-pressure regions. A general design is presented
in the body of the report for a revolving closure. Such a door could protect the
complete interior of such an installation against the shock effects resulting from
a nuclear detonation. The closure will be openable after exposure to blast and
would not be adversely affected by debris within the tunnel. Power requirements
will be relatively small. Cost estimates are presented.

AFSWC-TR-59-57   Confidential Report
Armour Research Foundation   Contract AF 29(601)-1168

INVESTIGATION OF SILO LININGS

Some of the aspects of the problem of determining the response of vertical underground silo linings to blast-induced loads are considered. These include the response of circular cross sections to radial pressure, the effects of differential horizontal displacement, and the analysis of the steady state motion of a rigid cylinder in an infinite elastic medium in the presence of a continuous plane wave.

The results show that increasing the wall thickness will decrease radial displacements of the lining but may not reduce the elastic bending stresses.

The investigation of the effects of differential horizontal displacement shows that circular cross sections remain circular during deformation and that large longitudinal bending stresses result from relatively small differential displacements.

The analysis of the motion of a rigid cylinder in an elastic medium indicates that the rigid body response to high frequency components of the disturbances in the free field will be greatly attenuated.

AFSWC-TR-59-56   Confidential Report
Armour Research Foundation   Contract AF 29(601)-1161

DESIGN AND ANALYSIS OF FOUNDATIONS
FOR PROTECTIVE STRUCTURES

A combined theoretical and experimental program was conducted to investigate the behavior of foundations under time-dependent loading.

The standard theoretical approaches describing soil failure under foundations are reviewed with respect to time-dependent loading. Equations are developed for failure of the soil under spread footings, taking into account inertial effects, pressures on the surface, and time-dependent forces. A method of solution for time-dependent loading on pile foundations is also developed. All the theoretical work employs standard soil parameters, the assumption being that means for selecting the appropriate values for these parameters will be provided by other current or future research.

The experimental work is of two types: (1) static loading of footings to obtain data not normally reported but vital for considering dynamic behavior, and (2) limited dynamic loading of footings. The static loading tests supply full

information on the load-displacement curves for given footings, establish the properties of the Ottawa sand used in the experimental work, and provide visual descriptions of footing behavior. The dynamic loading tests, in which the loading was achieved by dropping a known weight from a controlled height, supply abundant qualitative but only limited quantitative information. In particular, the observations of dynamic failure as contrasted with the observations of static failure lead to serious questions regarding the assumption that the mode of failure under static loading is descriptive of behavior under rapidly applied (dynamic) loading.

Design recommendations concerning footings for protective structures are made, based on currently available knowledge; it is recognized that continuing research into this general problem may soon provide better design methods.

The limitations of the research conducted on the program are described, and recommendations for future work are outlined.

AFSWC-TR-59-49   Confidential Report
Sandberg-Serrell Corporation   Contract AF 29(601)-1166

ANALYTICAL STUDIES, INVESTIGATIONS, AND PRELIMINARY
DESIGN OF DOOR AND FOUNDATION SEALS FOR
PROTECTIVE STRUCTURES

The purpose of the project was to study the problems connected with sealing protective structures against blast pressures, nuclear and thermal radiation, and ground water leakage. Because of the severe conditions encountered in nuclear weapon blast, it was reasoned that conventional sealing practices might be inadequate. Particular attention was given to the effects of both thermal and nuclear radiation on elastomers which might be used for seal materials.

A few design concepts are included in the report for various door and foundation configurations.

AFSWC-TR-59-48   Unclassified Report
Armour Research Foundation   Contract AF 29(601)-796

BLAST EFFECTS ON TUNNEL CONFIGURATIONS

Pressure measurements were made in tunnel-type models at the Air Force Shock Laboratory at Gary, Indiana. Tunnel overpressures were measured as a function of both geometric and free-stream blast wave parameters.

The tunnels were oriented such that the major axis of the tunnels subtended angles of 0, 45, and 90 degrees with the direction of free-stream blast flow. These tunnels were loaded by free-stream shock strengths in the range of 3 to 15. Pressure-time records (overpressure as a function of time measurements) were obtained at various positions within the tunnels. The effect of surface roughness on pressure attenuation was investigated utilizing a range of surface roughness factors from 0 to 7 percent. Geometric variations in the tunnel complex included various expansion chamber configurations, short 90 degree bends, and entrance restrictions.

It was shown that the peak overpressure, only one and one-half diameters from the tunnel's entrance, was of the order of 30 to 50 percent of the free-stream overpressure for 90 degree tunnel orientations. For tunnel orientations of zero degrees, the peak overpressure just inside the tunnel's entrance is greater than the initial free-stream overpressure, but considerably smaller than reflected pressure existing in the vicinity of the tunnel entrance. Overpressure near the entrance of the tunnels varied with both the orientation of the tunnel and with the magnitude of the free-stream shock strength. The attenuation of pressures further down the tunnels was a function of distance from the entrance, tunnel orientation, and tunnel geometric complex. Attenuation of pressure in small wall tunnels scaled according to the standard pressure-time scaling laws for the blast wave parameters tested. However, when wall roughness was introduced, pressure and time did not scale, especially for large diameter tunnels. In effect, the influence of wall roughness on attenuation became less pronounced as the absolute tunnel diameter increased.

AFSWC-TR-59-47   Confidential Report
Armour Research Foundation   Contract AF 29(601)-1134

GROUND SHOCK ISOLATION OF BURIED STRUCTURES

This report deals with the problem of alleviating the damaging effects of blast-induced ground shock on underground structures of the type presently contemplated for hardened missile sites. This first year's effort has been directed primarily toward the design and implementation of an experimental program utilizing miniature models of silo-like structures and several types of shock-isolation devices.

The model silos (rigid aluminum cylinder, 2 inches in diameter and 8 inches long) were emplaced in a bed of uniform Ottawa sand ; the ground disturbance was created by means of a small (0.02-lb) HE charge. Acceleration measurements were obtained at three points within the models. The isolation devices consisted of (1) a wrapping of a low-density (2-pcf) flexible polyurethane foam, (2) a simulated pile foundation for the model with an air void between the model and the sand, and (3) a simulated pile foundation for the model with pre-expanded polystyrene heads between the model and the sand.

The experimental technique was developed to the point where a satisfactory level of shot-to-shot reproducibility of effects was attained. Of the isolation

devices tested, the polyurethane foam material proved to be the most effective, reducing peak accelerations (of the unisolated model) by a factor of from 5 to 10. The stress level in the sand is estimated to be on the order of 1 psi. Various theoretical considerations relating to both the unisolated and isolated models are discussed.

AFSWC-TR-59-24   Confidential Report
Broadview Research Corporation   Contract AF 29(601)-1149

BLAST SHIELDING IN COMPLEXES

PART 2 - MEGATON WEAPONS

This report presents the results of the second part of an experimental investigation of the shielding effects of city complexes on the blast loading of structures both within the complex and in the region surrounding the complex. This study extends the previous work, in which kiloton weapons were simulated, to include the effects of megaton weapons.

The approach used was to expose small scale models of idealized complexes of city buildings to small high-explosive charges and to measure building loading and shock wave characteristics at various positions in and around the model.

For the test conditions investigated it was found that the shielding effects of the city complex in the region behind the complex tended to extend to greater distances for megaton weapons than for kiloton weapons. Within the city complex significant changes in loading were found to take place when the spacing between structures was comparable to or less than the structure height. A limited series of tests indicated that these loading changes are due to a relatively small number of structures surrounding the particular structure, rather than to the city complex as a whole. Although no full-scale results are available for comparison, it is felt that these scaled test results can be directly applied to real city complexes.

AFSWC-TR-59-18   Unclassified Report
University of Illinois   Contract AF 29(601)-468

AN INVESTIGATION OF THE BEHAVIOR OF DEEP MEMBERS

OF REINFORCED CONCRETE AND STEEL

The purpose of this investigation is to obtain information which will contribute to a better understanding of the strength and behavior of deep beams of reinforced concrete and steel subjected to slowly and rapidly applied loading, and to develop means for the prediction of this behavior.

This report contains the following:

(1) A thorough survey of the literature pertaining to the behavior of deep beams subjected to static and dynamic loads; (2) the results of static tests of twenty-three simply-supported, deep, reinforced concrete beams, fourteen under uniform loading and nine with a single concentrated load at midspan; (3) the results of dynamic tests on two simply-supported, deep, reinforced concrete beams; and (4) the results of one test of a deep, steel beam of I-shape cross section subjected to slowly applied uniform loading. Experimental results are compared with theory.

AFSWC-TR-59-10   Secret Report
Paul Weidlinger, Consulting Engineer   Contract AF 18(600)-1638

ON A METHOD OF AMPLIFICATION OF THE DYNAMIC
STRENGTH OF STRUCTURES

This report presents a description and analysis of a dynamic device which is capable of significantly increasing the dynamic strength of structure subject to very high intensity nuclear blasts. The amplification of the strength is obtained by providing a large movable mass over the structure to be protected. Under the blast the mass descends and exerts a pressure of predetermined duration and intensity on the structure which is significantly less than the intensity of the peak blast pressure itself. The motion of the protecting mass is retarded by forces provided by the blast pressure itself.

Analytical methods are presented governing both the mechanical and thermodynamic response of the device. Various applications to shelters are shown and a numerical example of the design of a particular shelter is given.

AFSWC-TR-59-9   Unclassified Report
University of Illinois   Contract AF 29(601)-464

ANALYSIS AND DESIGN OF DOMES, ARCHES AND SHELLS

Part 1 of this report is concerned with the development of a numerical procedure for the computation of the dynamic response of an elastic spherical shell when subjected to transient uniform pressure. This procedure is based upon the development of a discrete mechanism which replaces the continuous shell, said mechanism containing both bending and membrane resistance and large deformation effects. A numerical procedure is developed for obtaining the dynamic response of the mechanism, and a code is programed which makes the analysis on a digital computer. This program for an electronic digital computer

is presented in flow diagram form enabling an experienced programer to convert the order code to any type of computing facility. Using the program for the digital computer, certain parameters were investigated and the significant results and conclusions presented.

Part 2 of this report is concerned with the analysis of a membrane spherical shell by a discrete framework approximation. Equivalent areas of bars are derived on the basis of equivalent stiffness under identical loading. The framework is analyzed for natural modes and frequencies and the response of the framework to triangular blast loading is obtained by linear superposition of normal modes. Time histories of displacements are converted to time histories of bar forces which are combined to yield the shell stresses. A short digital computer program is written to superpose modes and to compute shell stresses. With the use of the program for the digital computer, certain parameters were investigated and the significant results and conclusions presented. Another digital computer program is independently developed in Appendix C as appended to Part 2 to compute the dynamic response of the same framework model. The flow diagram for this digital computer program is also presented, enabling a programer to convert the order code to any type of computing facility.

In Part 3 of this report is presented an exact analysis of the free vibration of an elastic membrane spherical dome of arbitrary radius, material, and total opening angle. The equations of motion are derived by substitution of the D'Alembert inertia forces into the static equilibrium equations. Expressions in terms of trigonometric and Legendre functions for the displacements and stresses during vibration are given. A table of the natural frequencies of vibration for various values of the opening angle of the shell is presented. The displacement vectors for the first five modes of symmetrical vibration of a hemispherical dome also are tabulated.

AFSWC-TR-59-3   Confidential Report
Armour Research Foundation   Contract AF 33(616)-2534

CROSS-REFERENCED LISTING OF EXPERIMENTAL DATA

ON THE BLAST LOADING OF STRUCTURES

A bibliography and cross index file of data dealing with pressure-time blast measurements on model structures is presented. It deals with the results of nuclear, high explosive, and shock tube tests.

Data have been abstracted and filed. For each case treated, values of critical parameters in the following groups are given; (1) blast parameters, (2) model parameters, (3) scale size, (4) instrumentation, (5) test results, (6) agencies involved, and (7) publications available. Each case treated is assigned a case number and filed according to the program from which it was derived. In addition, each case has been assigned an address. The address is a code consisting of letters and numbers and is defined in terms of the model shape and orientation; the location of the instrumentation; blast wave parameters

such as the wave peakedness, shock strength, and reflection type (Mach, regular, etc.); and type of test (nuclear, high explosive, and shock tube).

The bibliography consists of two main portions, (1) the Text, and (2) the Catalog. The Catalog is subdivided into three parts, namely: Part 1, the Address File; Part 2, The Data Sheets; and Part 3, The Notes and References. The text and Parts 1 and 3 of the Catalog are presented in Volume I. Part 2 of the Catalog is presented in Volumes II, III, and IV, which contain the Data Sheets for nuclear, high explosive, and shock tube tests respectively.

Utilizing this system of addresses together with the data sheets, one can determine the existence and whereabouts of certain data, knowing only the range in the type of variables described above. Furthermore, specific features of the blast wave, model, and instrumentation used can be determined directly from the data sheets.

AFSWC-TR-59-2   Secret Report
American Machine & Foundry Company   AF 33(616)-2522

PROTECTIVE CONSTRUCTION

Part 1. Summary.

This is the technical report of an investigation into the design of protective structures capable of accommodating one or more long-span aircraft and protecting them from nuclear blast at overpressure levels up to 100 psi. The detailed investigations of dome and arch structures are presented in this volume. Blast pressures, thermal and ionizing radiation effects, and relative economy of construction were considered.

Part 2. Technical Report.

This is the summary of the final report of an investigation into the feasibility and design of protective structures capable of accommodating one or more long-span aircraft and protecting them from nuclear blast at overpressure levels up to 100 psi. Domes, arches, and component enclosures (planform) were investigated in some detail; underground caverns and catenary structures were investigated only to the point where the inherent superiority of the other structures was clearly demonstrated. Blast pressure, thermal and ionizing radiation effects, and relative economy of construction were considered. Conclusions reached provide guidance in the selection of a structural configuration to protect a specific weapon system at a given pressure level. A summary of the preliminary results of full-scale field tests of domes conducted in Operation PLUMBBOB is included.

Part 3. Mathematical Analysis.

This part reports in detail the mathematical investigation which were conducted on the project and the reduction of the results obtained to simplified formulae.

AFSWC-TR-58-49   Confidential Report
University of Michigan   Contract AF 29(601)-467

DOORS AND ACCESS OPENINGS TO PROTECTIVE STRUCTURES

    Preliminary investigations of door-system requirements for dome, arch,
silo-type, and rectangular protective structures for aircraft are described.
Structural analysis, design, door removal systems, door economy, and con-
tinuity connections between main structure and door are considered. Each of
these items is only touched upon and much work still remains before definite
conclusions can be reached. Proposed future work on the above-mentioned
items is outlined.

AFSWC-TR-58-48   Unclassified Report
Atlantic Research Corporation   Contract AF 29(601)-431

DESIGN AND DEVELOPMENT OF A NET FORCE SENSOR

    The objective of the work reported here was to design and construct a proto-
type of a device to be used in measuring the aerodynamic forces on a model
structure installed through the floor plate of the Air Force 7-inch diameter shock
tube at Gary, Indiana. The design concepts and development status of the device
are described in the report.

    The work done thus far has revealed no fundamental technical reasons for
abandoning the approach to the design of the net force sensor described in the
report, although significant additional development would be needed to produce
a device which provides all the desired characteristics. In particular, some
means must be found to increase the load capacity of the transducer, and a closer
impedance match between model and support should be provided.

AFSWC-TR-58-28   Secret Report
University of Michigan   Contract AF 29(601)-467

PROTECTIVE ARCH STRUCTURES

    Arch structures, employing "catenary-arch" construction, are proposed to
protect aircraft against nuclear attack. A general description of the catenary-
arch structure, including brief discussion of the doors and other major structural
components, is given. Various methods of door removal are discussed and the
advantages and disadvantages of these methods are noted.

Rough estimates of the section requirements of the main structural com-
ponents are obtained on the basis of a number of simplifying assumptions relative
to the blast load and structural behavior.

The loading problem through a range of overpressures is discussed, and
the methods and assumptions used to estimate the blast loads transmitted to the
structure are presented. The approximate methods used to obtain estimates of
the structural requirements are given, and equations pertaining to the design of
the arch ribs are summarized. Cost estimates are given for each structure and
condition of blast loading considered, and the major cost factors are discussed.

AFSWC-TR-58-23   Secret Report
In-House Report

FEASIBILITY STUDY OF AN ABOVE-GROUND HARDENED HANGAR

An initial concept for what appears to be a practical and economically attrac-
tive protective shelter for aircraft has been devised by the Structures Division
of the Research Directorate, Air Force Special Weapons Center. This is the
initial concept for an above-ground hardened hangar to protect aircraft as large
as the B-52. The hangar can be built for only a fraction of the cost of the air-
craft which it shields. Such a structure depends, for its operational applicability,
upon a fast operating, structurally efficient, and relatively inexpensive door
whose properties are described in this report. Further engineering research,
especially on certain components, is necessary before final design can be under-
taken.

AFSWC-TR-58-5   Unclassified Report
University of Illinois   Contract AF 33(616)-3780

AN INVESTIGATION OF RIVETED AND BOLTED COLUMN BASE
AND BEAM-TO-COLUMN CONNECTIONS UNDER SLOW
AND RAPID LOADING

This report contains a description of slow and rapid load tests   riveted
and bolted column-base and beam-to-column connections, and the   ilts which
were obtained. Measurements of load, deflection, strain, and acc   ation were
taken to evaluate the resistance characteristics of the connections.

The small number of specimens and variety of connection typ(nited the
scope of the investigation. The tests clearly indicated that the rat   deform
tion had an effect on the resistance of the connection; rapidly defor   specin ns
had a greater resistance at a given deflection than those tested slo   In th(

tests, the type of fastener, rivet, or high-strength bolt had little effect on the moment-rotation characteristics of the connections studied. With respect to the evaluation of specific moment resistance characteristics of connections subjected to rapid load, this limited pilot study served only to indicate the nature of the resistance function which could be expected for connections of the type tested.

Also presented in this report is a procedure for evaluating the resistance of a frame with semi-rigid connections as it is loaded into inelastic range. The method of analysis is such that the resistance characteristics of the connection, as well as that of the members, are taken into consideration. The method is of particular interest from the research standpoint since strain hardening is included.

AFSWC-TR-57-45　　　　　　　　　　　　　　　　Unclassified Report
University of Michigan　　　　　　　　　　　　　Contract AF 29(601)-467

THE RESPONSE OF ... R BUILDINGS TO BLAST LOADS

This repor! . concerned v the development of relatively simple analytical techniques for | ·licting the r(·nse of multistory buildings to blast loads, in terms of collap· ·ir no collaps. The scope was confined to steel-frame buildings, and the c· ·onent of lon· to vertical blast was not considered.

In developi· ·he procedur ·he properties of the structure and of the blast load are a ·oximatcd m· ·natically. Determining the response of the structure is th(·problem in ·ration of a system of nonlinear differential equations, whic accomplisi· ·y high-speed digital computer. Thereby, a reasonably goo· ·trayal of tl· ·ponse is obtained. To simplify the procedure, an "equivalent ·o-degree-o· ·dom system" is proposed, which is derived from the prop· ·of the stru· ·, and which has a response comparable to that of the mult· ·ree-of-fr· ·system, in terms of collapse or no collapse. Integrating the ·ion of mot· ·r this equivalent system is a simple numerical integration pro! ·which c·.n ·ived rapidly with a desk calculator.

To correla· ·multi-deg· ·f-freedom and single-degree-of-freedom approaches, an ·s are made ·series of buildings representative of modern office buildings ·as multi ·e and single-degree systems. The results of these analysc· ·presente· ·e form of charts relating the parameters of blast overpress· ·yield of w· ·, building height, and initial impulse.

AFSWC-TR-57-32   Unclassified Report
University of Michigan   Contract AF 29(601)-467

PROCEDURES AND SPECIFICATIONS FOR EXPERIMENTAL
DETERMINATION OF LOAD-DEFLECTION CHARACTERISTICS
OF FULL-SCALE BUILDINGS

During the course of new highway or new building construction, it is some-
times necessary to destroy existing buildings. With cooperation of proper
authorities these buildings may become available for the purpose of full-scale
static and dynamic testing. In the event that structures and funds do become
available, it is desirable that a general guide in the form of specifications and
test procedures be available to expedite setting up and carrying out the tests.

This report outlines procedures for conducting static and dynamic tests on
full-scale structures. Buildings which were considered for testing were of steel
or reinforced concrete construction, and were either single-story industrial
structures or in the range of from three to five stories. The report includes
specifications covering the selection, inspection, and modification of the test
structures; discussion of vibration, shock, pulldown, and story shear tests;
and description of methods of loading, instrumentation, and recording. Estimated
costs for the various major items of required test equipment for the static and
dynamic tests are tabulated in an appendix.

AFSWC-TR-57-29   Unclassified Report
Broadview Research Corporation   Contract AF 33(616)-3778

BLAST SHIELDING IN COMPLEXES

This report presents the results of an experimental investigation of the
shielding effects of city complexes on the blast loading of structures both within
the complex and in the region surrounding the complex.

The approach used was to expose small-scale models of idealized complexes
of city buildings to small high explosive charges (simulating about 140-KT
weapons) and to measure building loading and shock wave characteristics at
various points in and around the models.

For the test conditions investigated, it was found that the shielding effects
of the city complex on the shock waves were limited to the complex itself, and
to its immediate environs. At relatively small distances behind the complex the
shock waves exhibited virtually complete recovery. Within the complex, how-
ever, significant changes in loading were found to take place when the spacing
between structures was comparable to or less than the structure height.

This study was undertaken because city complexes are considered of primary
importance as potential targets of both friendly and enemy forces, and because

up to the time of this study, attention had been focused on the blast loading of single structures, with at most one shielding structure, and with little regard for the influence of additional buildings in their surroundings on that loading.

AFSWC-TR-57-23   Unclassified Report
University of Illinois   Contract AF 33(616)-170

STATIC AND DYNAMIC TESTS OF STEEL FRAME STRUCTURES
INTO THE INELASTIC RANGE OF DEFORMATION

The experimental and analytical program which was conducted at the University of Illinois under Contract AF 33(616)-170 is summarized in this final report. The basic purpose of the program was the performance of tests and analyses to obtain basic information concerning the behavior of steel structural frames and elements when subjected to known static and dynamic loadings that produce extensive inelastic deformations. The various phases of the project and the major conclusions reached are described briefly. Abstracts of each of the Technical Reports produced are given in one Appendix and a tabulated summary of the tests performed are presented in another.

The conclusions presented in the report are listed below:

1. The actual resistance of a mild steel structural element to an imposed inelastic deformation increases with the rate of that deformation, and is also dependent upon the time involved.

2. In most of the specimen types in which it occurred, local inelastic buckling was less pronounced in the rapid tests than in the slow ones, which indicates that the effectiveness of the beam section was increased with the rapidity of deformation.

3. An axial load on a structural member decreases the ability of the member to resist lateral load, but does not affect appreciably the total resistance of the member to an external moment except in the limited range of deformation immediately following initial yielding.

4. The effect of shear upon the moment capacity of an 8 WF 58 section loaded laterally and slowly in the plane of the major axis was found to be negligible even for a beam having an equivalent cantilever span to depth ratio as low as 2. However, in a region of constant shear but gradient moment, the development of a general shear yielding condition in the web caused deflections considerably greater than those which resulted from concentrated yielding primarily caused by moment.

5. In most of the structural elements and models tested, the initial "elastic" region of the resistance-deflection relationship had a slope less than that derived

using elementary theory and assumed ideal conditions of support.

6. A static resistance-deflection function for a simple structural element or a relatively simple structure can be determined with good accuracy by using practicable approximations to relate strains to deflections, and then computing resistance on the basis of the known static stress-strain characteristics of the material involved.

7. For research purposes requiring good accuracy, an equivalent resistance-deflection function for a relatively simple structure subjected to rapid deformation can be determined in a manner similar to that mentioned above, using, of course, the dynamic properties of the material in the determination of the resistance. The procedure should be such that the equivalent resistance is computed using instantaneous material stresses at the critical sections which are compatible with the strains, straining rates, and times involved. The total resistance so determined (which does not include inertia forces) is actually a function of time as well as displacement and, therefore, is strictly valid only for the particular case considered, or for others very similar as regards loading function and structural configuration.

8. However, since the effect of delayed yielding is probably important only in cases of short duration impulse, and since the general yielding resistance of mild steel is relatively insensitive to changes of straining rates within one or two orders of magnitude, suitable accuracy can be obtained in most practical problems (where the dynamic loading function is seldom known with great accuracy) simply by increasing the static inelastic resistance of the structure in accordance with the straining rates estimated to exist at critical locations in the structure as it responds to the rapid loading imposed.

9. Methods were developed for analyzing indeterminate frame structures deformed inelastically. In these procedures the resisting moments throughout the structure which correspond to a compatible deflection configuration are determined. The methods are illustrated with the solution of "static" problems. However, they could be used with slight modification in the time-wise step-by-step solution of problems involving structural response under rapid loading. Their use in this manner would be most practicable with the use of a high-speed digital computer.

10. The analytical procedures which have been developed on this program were intended for use in research applications. However, they should be useful not only in the planning of testing programs and the evaluation of experimental results but also in determining the relative accuracy of simpler methods which are more suitable for purposes of design and routine analysis.

AFSWC-TR-57-22   Unclassified Report
University of Illinois   Contract AF 33(616)-170

60 KIP CAPACITY SLOW OR RAPID LOADING APPARATUS

To obtain dynamic tests of structures or structural components in the lab-
oratory it was necessary to design and construct a machine which could provide
the required load and stroke. Operating and loading characteristics of three
such machines are described in this report.

The 60 Kip pulse loading machines described in this report have been used
successfully in testing beams of both steel and reinforced concrete and in apply-
ing lateral loadings to steel columns. They have also been used in the study of
beam-to-column connections and in the study of simple column base connections.
All of the tests were conducted such that the specimen either collapsed or was
deflected well into the strain hardening range of the specimen material.

A load having any selected value up to 62,800 pounds can be applied either
slowly or rapidly in either tension or compression. The duration of the peak
load may be varied from as little as 0.008 second to many hours.

AFSWC-TR-57-21   Unclassified Report
University of Illinois   Contract AF 33(616)-170

SLOW AND RAPID LATERAL LOADING TESTS OF SIMPLY
SUPPORTED BEAMS AND BEAM COLUMNS

The two major purposes of the program described in this report were (1)
to determine experimentally the resistance of several beam and beam columns
specimens to inelastic deformations applied slowly and rapidly, and (2) to corre-
late these resistances with the static and dynamic properties of the materials
from which the specimens were made.

The results obtained indicate that, beyond the static elastic limit, the resist-
ance of a mild steel beam or beam-column to a lateral displacement produced
rapidly is greater than that corresponding to the same lateral displacement pro-
duced slowly; and that the increase in the resistance of a beam with the rapidity
of the lateral deformation can be explained, within reasonable limits not greatly
exceeding experimental error, by consideration of the experimentally determined
dynamic properties of the specimen material which include delayed yielding and
rate of general yielding behaviors of mild steel.

AFSWC-TR-57-9   Confidential Report
Broadview Research Corporation   Contract AF 33(616)-160

EFFECTS OF TOPOGRAPHY ON SHOCK WAVES IN AIR

No attempt is made in this final report to describe in full detail the 4 years
of research conducted under this contract, since such complete information has
already been published in a series of Interim Reports (enumerated in Appendix A
of the report). Rather the primary aims of this report are (1) to give a succinct
summary of the important results, and (2) to suggest methods for their employ-
ment. The pressure range covered in the report is, for the most part, those
pressures up to around 30 psi incident pressure.

Experimental determinations have been made of the alterations in shock wave
overpressures near the surface of the earth due to the configurations of that sur-
face provided by natural topography. The shock wave overpressures from mini-
ature charges of high explosive were recorded as a function of time with gauges
imbedded in three-dimensional topographic models.

In regions where Mach reflection would occur on a plane surface, the effects
of nonplanar topography are dependent primarily on the inclination of the slopes
encountered and secondarily on the shock wave overpressures incident on those
slopes. In general, falling slopes cause overpressures to be reduced, with a
greater reduction the greater the slope angle and the smaller the incident pres-
sure; while rising slopes cause overpressures to be increased with a greater
increase the greater the slope angle and the smaller the incident pressure.

An outline procedure to follow for predicting the effects of topography on
shock waves in air is presented as an aid to target analysis.

AFSWC-TR-57-1   Secret Report
Armour Research Foundation   Contract AF 33(616)-2540

TWO- AND THREE-DIMENSIONAL SHOCK TUBE LOADING STUDIES

ON MODELS OF OPERATION KNOTHOLE PROGRAM 3

The objective of this program was to obtain a more complete correlation
between blast loading data obtained from Program 3 of Operation Knothole and
scaled shock tube models of the structures. The structures tested were solid
rectangular parallelepipeds, horizontal cylinders, and vertical cylinders. This
report compares the pressure-versus-time records and related phenomena from
Operation Knothole Program 3 with those from scaled models of the same struc-
tures tested in a shock tube. The testing was accomplished by utilizing the Air
Force 2-foot-diameter shock tube located at Gary, Indiana.

There are many factors to take into consideration in order to come to any definite conclusions with regard to scaling between shock tube and field tests; however, after a careful examination of all the data, it is concluded that if the free-stream pressure records are corrected for differences in incident pressure-time curve shapes between model and field tests, the records on the various surfaces do actually scale within the meaning of present scaling laws. Thus, the present loading schemes which were obtained primarily from shock tube tests are applicable to field test conditions.

The pressures on the surface consist of two components, the free-stream and the dynamic component. Since the diffraction phase is primarily influenced by the free-stream component, there is further confirmation of scaling of diffraction loading. This, however, is not surprising, since free-stream pressures were expected to scale if the ground surface in the field was sufficiently ideal for comparison with shock tube conditions.

The scaling of dynamic pressures is one of the main results of this study. An analysis of the comparison of the shock tube records revealed the fact that the net pressures (pressure at a point minus free-stream pressure), that is, the product of the pressure coefficient and the dynamic pressure, at corresponding scaled times were nearly identical, at least within the experimental errors involved. This analysis included only pressure-time records which were considered reasonable, based upon our past knowledge of the loading phenomenon. As a consequence of the near identity of these point loadings, their integrated effect, i. e., the net load, also agrees in the drag phase.

AFSWC-TR-56-48   Confidential Report
Stanford Research Institute   Contract AF 33(616)-226

AIR BLAST LOADING ON STRUCTURES

The general objective of the Air Force empirical blast study program was to develop a technique for the prediction of airblast pressure loading on full-size targets exposed to full-size nuclear explosions. This report deals principally with the series of model tests conducted at Beale Air Force Base (California) during 1956. These tests include pressure measurements on cubical and cylindrical targets subjected to airblast loading from airburst detonation of TNT.

The data obtained at the Beale Site are presented and analyzed with respect to repeatability, effect of shock strength, and effect of cylinder height. The results are compared with data from shock tube loading tests from the DRAGON Coyote Canyon test series of 1953, and from full-scale nuclear tests.

AFSWC-TR-56-47   Unclassified Report
University of Illinois   Contract AF 33(616)-170

A METHOD FOR THE ANALYSIS OF FRAMES SUBJECTED TO
INELASTIC DEFORMATION INTO THE RANGE OF STRAIN HARDENING

This report presents a method for determining the resistance of frame structures composed of elements having individual resistance deformation characteristics of any monotonically increasing form that can be described graphically. The method is very useful in research applications and is the only available method for the analysis of frames subjected to deformations into the range of strain hardening.

A simplified procedure for the analysis of independent frames using moment distribution with bilinear approximations to the moment-end slope relationships is presented in the appendix.

AFSWC-TR-56-46   Confidential Report
American Machine and Foundry Company   Contract AF 33(616)-2285

TRANSIENT DRAG AND ITS EFFECTS ON STRUCTURES

This report presents the results of a study of the drag forces on typical structural sections that are not to be found in the literature. The influence of section parameters, principally corner radius, have also been examined, as have the effect of interference obstacles and the inclusion of the item in a structural complex. The flow of gas in the so-called steady state portion of shock tube flow was also examined to some extent.

There is basic information in this report for further test work necessary to solve the ideal wave transient drag loading problem. No definite conclusions are given; however, recommendations for future transient drag work are included.

AFSWC-TN-61-16   Unclassified Report
Armour Research Foundation   Contract AF 29(601)-796

TESTS ON ATLAS BLAST VALVES

The WS-107A-1 Silo Blast Closures, 16-inch and 42-inch, were subjected to a series of performance experiments. These performance experiments were designed to simulate the actual operating condidtions and/or environments

to which the closures would be subjected during normal operation. The closures were evaluated when subjected to air blast loading, prolonged cold and hot environments, and repeated use or cycling.

The 16-inch closures reacted satisfactorily to all the performance experiments with the exception of cold environments. They were subjected to an air blast loading of 120 percent of the anticipated maximum design blast load without failure. The temperature of the closure was raised to 200 °F and held for a 72-hour period; it operated satisfactorily afterward. The closures were also repeatedly operated through 1,500 cycles without failing. During the cold environment experiments, pressure leaks in the hydraulic system of the closures developed at approximately 0 °F. These pressure leaks resulted from the shrinkage of the Teflon seals in the system.

The 42-inch closures responded satisfactorily to only the hot environment experiments. The temperature of the 42-inch closures was raised to 300 °F before any failures occurred. Pressure leaks in the hydraulic system occurred when the closures were air-blast loaded. These leaks were evident even at 50 percent maximum design air blast load. Extensive damage developed during the repeated cycling experiments. The pipe fittings and copper tubing of the hydraulic system were continually cracking and the bolts and screws holding various components together were shearing. The temperature of the closure was lowered to approximately -20 °F before pressure leaks developed in the hydraulic system.

DESIGN AND ANALYSIS OF FOUNDATIONS
FOR PROTECTIVE STRUCTURES

The behavior of footings subjected to time-dependent forces is the subject of continuing research. The approach to this research is twofold; theoretical and experimental. This interim report is concerned with the experimental results and comparisons to the theoretical approaches.

Two- and three-dimensional footings on Ottawa sand were loaded dynamically using the loading apparatus and instrumentation developed for this program. The two-dimensional experiments permitted observation of the behavior on loose and dense sand subjected to vertical, inclined, and eccentric dynamic loads. The three-dimensional experiments provided force-time and displacement-time records of the behavior on dense sand of vertically loaded footings.

These experiments demonstrate that the theories developed previously on this program are not satisfactory. They also indicate the direction to be taken in future theoretical research.

In an attempt to consider additional soils, California sand and clays were studied. A series of static loadings of three-dimensional footings was conducted on California sand. Static and dynamic loads were applied to two-dimensional footings on clay. It was established that the static loads were truly static by experiments conducted at low rates of loading.

AFSWC-TN-61-7   Unclassified Report
In-House Report

BASIC INTERACTION CONSIDERATIONS

Two recently published theoretical studies which treat a two-dimensional interaction in an elastic medium between a plane stress wave and a circular hole are compared to a classic static solution and a newly published experimental solution. These solutions have special meaning since they were obtained independently and are in excellent agreement within their range of applicability. Basically, the two theoretical solutions predict an increase over static stress concentrations of approximately 9 percent. The experimental study produced an average increase of 11.4 percent. Maximum hoop stresses occur within 4 to 5 transit times and then approach computed static values. Until more meaningful experimental and theoretical studies are applied to real materials, it may be possible to use these extremely simplified solutions as a first approximation to the problem of unlined cavities in competent rock.

AFSWC-TN-61-6   Unclassified Report
National Engineering Science Company   Contract AF 29(601)-2838

A THEORETICAL STUDY OF STRUCTURE-MEDIUM INTERACTION

A study is presented in this report of the interaction of a plane longitudinal wave of stress with a hollow cylindrical shell embedded in an infinite elastic medium. In contrast to previous studies of this type, the shell is not taken as either infinitely rigid or infinitely thin (cavity) but is given finite dimensions (with the assumption of thin shell geometry) and finite density and elastic properties differing in general from those of the medium. Both steady-state and impulsive waves were considered. For the steady-state case, a general series solution was obtained for arbitrary properties of the medium and shell. A procedure was outlined for obtaining transient (pulse) solutions from steady-state solutions. The application of the Laplace transform method was outlined and certain formal results obtained; in the case of a cylindrical cavity the approximation valid for a slowly varying wave was obtained explicitly. A method for calculating Fourier-Mellin inversion integrals was outlined and should prove of great assistance in obtaining numerical solutions to specific transient problems, with the application of automatic computing techniques.

AFSWC-TN-60-39   Unclassified Report
In-House Report

AN EXPERIMENT ON SOILS LOADED DYNAMICALLY
BY A SHOCK TUBE

The Air Force 6-foot shock tube was used to pass air shocks across the upper surface of different soils samples of controlled properties. Gages of available types were buried within the samples or mounted upon the supports of the sample container. The tests were intended eventually to develop into an experimental study of energy transmission in soils samples of all types, first by investigation of the experimental difficulties apparently common to any such tests. The apparatus and procedures are described, and data from a few tests are presented. The compaction observed in the samples is described, and certain preliminary results are qualitatively discussed, including shock transmission in the sample pores, the velocities and attenuation of transmitted waves, and the extent to which differences in sample properties were reflected in the various measurements.

AFSWC-TN-60-36   Unclassified Report
Armour Research Foundation   Contract AF 29(601)-2561

DESIGN AND ANALYSIS OF FOUNDATION
FOR PROTECTIVE STRUCTURES

The behavior of footings subjected to time-dependent forces has been the subject of continuing research. The ultimate bearing capacity under such loading conditions and the dynamic behavior beyond this ultimate capacity are both of interest. An attempt has been made in the subject investigation to combine and correlate laboratory experiments with theoretical studies.

Two- and three-dimensional experiments have been conducted on small footings in the laboratory to observe their behavior and to obtain quantitative information. An apparatus was developed for applying dynamic forces to the footings. This apparatus, which is relatively simple, has made possible the application of loads having various rise times, decays, and durations. Force-time and displacement-time records have been obtained in forms suitable for analysis, and Fastax movies of footings failing under dynamic loads have also been taken.

The behavior of footings subjected to dynamic loads has been studied analytically also. The possibility of applying the plasticity theory or limit analysis has been considered. Other loadings and various failure modes also have been investigated. Use will be made of the experimental data in conjunction with this theoretical work during the remainder of the program. Based on this work, additional experimental and/or theoretical research will be conducted as required.

AFSWC-TN-60-30   Unclassified Report
Paul Weidlinger, Consulting Engineer   Contract AF 29(601)-2855

ATTENUATION OF STRESS WAVES IN BILINEAR MATERIALS

The attenuation of plane stress waves generated by a decaying surface
pressure in a bilinear medium is investigated, to obtain an approximate solution
to the problem of a medium with a stress strain diagram of positive curvature.
Wave equations are derived, and it is demonstrated that, beyond a given distance
from the surface, the intensity of the peak stress and particle velocity depends
only on a single parameter. This result is of significance in establishing the
relevant physical characteristics of granular soils which are subjected to very
high intensity nuclear surface blast pressures.

AFSWC-TN-60-20   Unclassified Report
Stanford Research Institute   Contract AF 29(601)-1948

A GLOSSARY OF GEOPLOSICS:

THE SYSTEMATIC STUDY OF EXPLOSION EFFECTS IN THE EARTH

With the growing interest in ground motion in the design of underground
protective construction, in earth moving, and in predictions for field experi-
ments, engineers and scientists must be conversant with the language of geo-
plosics, its theories and phenomena. This glossary is an attempt to provide
within a single cover a reservoir of that special language.

The terms and their definitions have been selected to include not only the
dynamic aspect of ground motion (acceleration, velocity, and displacement) but
also the permanent effects of that motion (craters, residual strain, permanent
displacement). Also included are terms from related fields, such as seismology,
which may not now be in widespread use but which are likely to be used as ground
motion research increases.

Many words contained herein already have standard meanings in other con-
texts and are applied to ground motion with their usual meanings intact. Some
have a definition in one field and have taken on a different meaning when applied
to ground motion; and others, as standard terms in this field, have had their
meanings brought up to date. Still others, in the interest of unambiguous
communications, are frankly coined to describe heretofore unnamed phenomena.

IMPROVEMENT IN THE CAPABILITIES OF THE AIR FORCE
6-FOOT SHOCK TUBE BY SEVERAL ORDERS OF MAGNITUDE

A new manner of arranging strands of primacord (the shock-producing agent) in the Air Force 6-foot shock tube has increased the capability of the laboratory to produce clean shocks equal to those observed in detonations of nuclear weapons. The old arrangement furnished clean shocks equal to those produced by up to 1/8 KT explosions and up to 70 psi overpressure. The new arrangement gives shocks in the test section equal to those coming from up to 5 KT detonations and up to 100 psi peak pressure with the tube as it is, and in its present location, where it must be operated with closed ends.

The report shows how it is possible to obtain a shock in a similar, but vastly improved tube, that reproduces the clean blast wave conditions of megaton detonations up to 400 psi peak overpressure.

A SUMMARY OF REPORTS PRODUCED UNDER ARDC PROJECT 1080,
"PROTECTIVE CONSTRUCTION AND TARGET VULNERABILITY
AND ITS PREDECESSORS"

This report summarizes the general objectives to be attained by each present task of Project 1080 and the approach that research intends to take in attaining them, as well as the objectives and conclusions of the documents so far resulting therefrom. The Structures Division of the Research Directorate, Air Force Special Weapons Center has the technical responsibility for the project and its tasks. The purpose of this report is to summarize the work of this Structures Division, its predecessors, and its contractors in blast effects research, in order that other interested agencies may be made cognizant of the results obtained so far and, in turn, to effect closer coordination and cooperation. Some of the work mentioned was performed under tasks that are now terminated and not specifically mentioned.

Individual contracts and pieces of work have been grouped under their respective general fields of research, with the exception of reports prepared under Program 3 of Operations GREENHOUSE, BUSTER-JANGLE and UPSHOT-KNOTHOLE and the miscellaneous reports prepared under ad hoc contracts. These latter reports have been grouped in separate chapters.

AFSWC-TN-59-8   Unclassified Report
University of Illinois   Contract AF 29(601)-468

REVIEW OF THE LITERATURE PERTAINING TO THE
BEHAVIOR AND DESIGN OF DEEP STRUCTURAL MEMBERS

After a comprehensive literature survey into the field of deep beams, 80 of the most pertinent references were selected for presentation in this document.

Roughly half of these pertain to reinforced concrete deep beam theory. No conclusions were forthcoming from the study of this group although voluminous data of failure mechanics were obtained for diverse configurations of reinforcement. These data can be used as a guide in organizing future testing.

Another group of references concentrates more on moment-shear interaction in medium-thick beams (1:6 ratio), from which information on web reinforcement was obtained. Unfortunately, the theories used in this group of reports were for an uncracked, idealized material. The big void in this particular phase is in the behavior of beams of real materials.

Still another group of reports reviews the response of small-scale beams of conventional length-depth ratios to impact loading.

The last group of references are papers on the behavior of deep steel members. Considerably more seems to be known in regard to moment-shear-plastic flow interaction in steel. At least, the subject can now be approached analytically as a result of the work of W. J. Hall and others. Laboratory check points are needed, however.

AFSWC-TN-59-4   Unclassified Report
American Machine & Foundry Company   Contract AF 33(616)-2457

SHOCK TUBE AIR VELOCITIES

Flow velocities behind a shock front were measured in a shock tube by observing the displacement of heated air bubbles generated in the flow by a series of sparks. Strip records of the displacement were obtained by Schlieren photography. These provided graphic velocity-time histories of the flow which were evaluated quantitatively and compared with theoretical values.

The flow measuring method proved to be practicable. Refinements in the recording components would greatly enhance the capabilities of the method. Flat top shocks only were investigated.

AFSWC-TN-58-26   Unclassified Report
Armour Research Foundation   Contract AF 29(601)-796

AIR BLAST LOADING ON ARCHES AND DOMES

Tests have been conducted on solid models of arches and domes in the Air Force 6-foot shock tube in Gary, Indiana. Primacord high explosive was used to generate shocks ranging in strengths from about 1.3 to 7.0. This resulted in both subsonic and supersonic flows behind the shock front.

Two arches and four domes were tested. The two arches were sections of circular cylinders. The central angles of the arches were equal to 120 and 180 degrees. The arches were oriented with flow normal to the axis of the cylindrical surface. The four domes were sections of spheres. The central angles of the domes were equal to 60, 90, 110, and 180 degrees.

Measurements of point pressures at various points on the surface of each model were made. Flush-mounted miniature barium titanate pressure sensors were used to obtain individual pressure-time records for each gage position.

The results obtained are in the form of pressure-time curves together with charts giving the numerical values of essential quantities. These quantities are normalized pressure and time values for critical points of the diffraction phase and drag coefficient for the pseudo-steady-state phase. Profiles showing the variation of these quantities with angle of incidence in the vertical plane are presented for the arches. Contour diagrams are utilized to express the variation of these quantities over the surface of the domes. Different curves which have shock strength as a parameter are shown when necessary.

AFSWC-TN-58-25   Unclassified Report
Armour Research Foundation   Contract AF 29(601)-796

INITIAL INVESTIGATION OF WAVE PROPAGATION
IN LARGE SOIL MODELS

Preliminary shock tube tests have been conducted to study the pressures recorded by barium titanate pressure sensors located in a moist clay model with one surface exposed to the pressure pulse of a transient air blast wave. Primacord was used to generate the blast wave.

A cylindrical model 15-3/4 inches in diameter and 36 inches long, containing 15 gages at various distances from the loads surface, was subjected to blast overpressures of 6.5, 10.5, 19.0 and 31.4 psi. Good records were obtained from 13 gages on each of four shots. The compression wave propagated through the soil exhibits a finite rise-time which increases with depth up to a depth of roughly one diameter after which it remains roughly unchanged. The time-of-arrival of the

wave front at a given depth was found to be independent of the air blast over-pressure, while the time-of-arrival of the initial peak pressure decreases with an increase in overpressure, largely as the result of reflections of the compressional wave from the sides of the model container.

The results appear to indicate that the shock tube is an effective device for loading large size soil models (dimensions of the order of about 1.0 to 5.0 feet) for controllable and reproducible impact loading. Furthermore, the overall performance of the barium-titanate-type pressure gage when embedded in moist clay seems to be satisfactory. Further tests should be conducted on models of this general type in redesigned containers.

AFSWC-TN-58-23   Confidential Report
Stanford Research Institute   Contract AF 29(601)-540

GROUND MOTION INDUCED BY NUCLEAR EXPLOSIONS
A STUDY OF FUNDAMENTAL PROBLEMS

This report presents results of a study directed toward delineation of a number of analytical and experimental approaches toward increasing knowledge of dynamic soil behavior with special references to the response of soil and rock subjected to nuclear air bursts, and the loadings which this response will impose on buried structures. The results of this study are intended to indicate useful avenues of further research which will ultimately provide more reliable design criteria for protective construction.

Three general areas of research were investigated: laboratory experiments to determine the dynamic properties of soil and rock; scaled HE field experiments; and mathematical theory of two-dimensional wave propagation.

Since knowledge of the dynamic properties of soils is very meager, research programs are necessary to develop laboratory techniques to correlate these dynamic properties with the various elements of soil structure. In addition, field testing techniques must be developed to measure the dynamic properties of soil, in situ.

A laboratory program is outlined which will lead to the determination of the dynamic compressive properties; however, three-dimensional wave propagation requires knowledge of dynamic shear properties as well. The latter problem has not been studied.

Conclusions pertaining to three-dimensional viscoelastic theory are presented.

Solution of the nonhomogeneous elastic problem was investigated and the three-dimensional viscoelastic theory is discussed in the report. The feasibility of an electrical network analog solution is shown to hold considerable promise. It is recommended that both the numerical and analog methods be developed

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simultaneously until it can be established which one will be sufficiently flexible to solve all of the problems that may be encountered.

AFSWC-TN-58-18   Unclassified Report
Armour Research Foundation   Contract AF 29(601)-465

INVESTIGATION OF WAVE PROPAGATION IN SEMI-SOLIDS

This research program had two main objectives: (a) further development of the experimental methods of dynamic photoelasticity and grids as a means for studying wave propagation phenomena in solids, and (b) development of a method for studying the performance of pressure gages, embedded in a specimen and subjected to an impact type of loading. The program was a continuation of a previous research program in which the Fastax camera in conjunction with soft model materials was introduced as a means for studying wave propagation.

During the course of the program, a microflash method was developed for recording photoelastic patterns and grid deformations simultaneously. A soft photoelastic material (Hysol 8705) was selected as the model material and its static and dynamic properties (physical and optical) were completely determined. By using the photoelastic pattern, the grid measurements, and the material properties, it was possible to determine stress distributions resulting from impact-type loadings. As an indication of the procedure to be used, the principal stresses along the vertical diameter of a disk subjected to a diametrical compressive impact loading were determined.

In another phase of the program, the use of the Fastax camera was continued and applied to the study of wave propagation phenomena in large plates subjected to air blast and explosive-type loadings. This series of tests clearly showed that a shock tube can be used in conjunction with photoelastic models for air blast studies. The fringe patterns obtained were satisfactory for studying the overall wave propagation phenomena. In regions where more detail was required than could be recorded on the 16 mm Fastex film the microflash unit gave suitable records.

The performance of barium titanate and diaphragm-type pressure gages embedded in soil or soft rubber specimens and subjected to impact loadings was studied. Pendulums were used for this purpose. In general, the barium titanate gages recorded a pressure which compared favorably with an independently determined pressure when the loading rate was high. The diaphragm gages seemed to perform better when low loading rates were used.

Gcneral Note on the summary of the three last-mentioned reports:

This is a basic research attempt to determine, in an idealized medium, phenomena which are of interest to protective construction in actual soils or rock. Indications are that this attempt will be at least partially successful and practically applicable.

GEOLOGICAL AND GEOPHYSICAL CONSIDERATIONS
FOR ICBM LAUNCHING SITE SELECTION

This study contains a discussion of the desirable and undesirable characteristics of the surrounding geology in which an underground, cylindrical shelter containing an ICBM may be situated. Different properties of soil and rock are investigated regarding their capability to absorb and/or redistribute dynamic energy induced by nuclear explosions using the sparse data from full-scale tests and small-scale high explosive tests.

General geological recommendations presented in the report are as follows:

(1) It is desirable that rock occur close to the ground surface. The rock should be igneous, metamorphic, or sedimentary having a good degree of uniformity

(2) Ground water in the soil or rock above the elevation of the missile platform is undesirable.

(3) The soil condition at ground surface should be firm enough to support construction operations.

The report states that unfavorable geological conditions can be designed out of the entire construction picture, but to do so will entail a decrease of the confidence in the adequacy and a considerable increase of the cost of construction. Five geological regimes are, then, recommended in the order of preference.

(1) Sound, uniform, igneous, metamorphic, or sedimentary rock, 300 feet or thicker overlain by predominately sand or gravel soils 100 to 200 feet in thickness.

(2) Sound, uniform, igneous, metamorphic, or sedimentary rock, 300 feet or thicker outcropping at the site and for appreciable distance around it.

(3) Sound, uniform, igneous, metamorphic, or sedimentary rock, 300 feet or thicker, overlain by more than 200 feet of predominately sand-gravel soils.

(4) Deep sedimentary soil, sand-gravel, at least 500 feet in thickness.

(5) Deep sedimentary clays, silts, shales, thinly bedded, intermixed, and at least 500 feet in thickness.

The report states that highly fractured, nonuniform, weak rocks of great thickness and water-filled silts, clays, thinly bedded, saturated shales, of solution-channeled limestone should be avoided. In addition, it is desirable that the climate be semiarid to arid, in order to avoid temporary major changes in ground water level.

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AFSWC-TN-57-37   Unclassified Report
Armour Research Foundation Personnel   Contract AF 33(616)-2644

OPERATION OF THE AIR FORCE SHOCK TUBE LABORATORY,
GARY, INDIANA

This report summarizes the activities of the Armour Research Foundation in operating the Air Force Shock Tube Laboratory at Gary, Indiana during the period 1 September 1956 to 30 September 1957. During the year, work was conducted on 13 separate programs. These dealt with loading on oil storage tanks, on mill building models, on blocks, cylinders and domes, in the interiors of model buildings, on idealized models of successive bents, on instrumentation equipment, and on annular rings as shock attenuators in tunnels, response studies on scaled model oil storage tanks, tests on a BRL field type "Q" gage, and the study of explosive decompression on aircraft equipment. Work on seven of these programs was performed wholly within the report period, while the others were performed only in part during this period. Two final reports, one technical memorandum, and four preliminary reports have been written for the Air Force as part of these programs. On two programs final reports were issued for outside agencies while raw data were turned over to outside agencies on another two programs. Five programs are currently in the testing or analysis phase.

In addition to routine maintenance of the laboratory, continual efforts have been made to increase the operating accuracy of the instrumentation equipment and to design and construct better pressure gages. These efforts have been reasonably successful. Improvements of the facility include a 94-foot extension of the 6-foot shock tube, reorientation of the existing 6-foot tube in the opposite direction to accommodate the extended length, installation, and equipping of an additional building to be used as office space and to house the 4-inch shock tube which is used for gage calibration, installation of additional equipment in and remodeling of the instrument room.

AFSWC-TN-57-32   Unclassified Report
American Machine and Foundry Company   Contract AF 33(616)-2457

NET-FORCE SENSOR RESEARCH

The objective of the research reported herein was to produce a working model or models of net-force sensors and to develop the technology of their fabrication and use. A net-force sensor is an instrument which measures the net blast force on an object as a function of time. It is used to study the blast loading on objects in the path of a blast wave.

On the basis of the research effort, the following conclusions were made:

(1) A cantilever beam net-force sensor can be constructed to measure transient force phenomena on a shock tube mode. A sensor of this type was constructed with a minimum of preliminary theoretical design analysis. It was used to measure the force on a rectangular bar model in the shock tube.

(2) The SLM pressure gage, which was used as the sensing element in the sensor, has outstanding possibilities for use in net force sensor construction. It permitted the construction of a rugged instrument which gave accurate data. The SLM gage has a high degree of sensitivity and has a high natural frequency.

(3) The net force sensor which was constructed demonstrated certain inadequacies which would have to be improved before it could be used as a practical instrument.

The principal disadvantage was the large amount of vibration superimposed on the force vs. time records. This effect was reduced by the experimental expedients of stiffening the beam and using a crude filter at the output. More refined cantilever beam design and filter analysis would be desirable.

Another inadequacy in the sensor is that the SLM gage is not used in an optimum manner. A more refined design, which would balance the output of the gage with the stiffness of the cantilever beam, could substantially increase the natural frequency of the sensor. This would increase the usefulness of the sensor in measuring transient phenomena and possibly alleviate the vibration problems.

(4) Future designs of net force sensors should not be limited to the cantilever beam concept. Sensors using multiple load-cell arrangements and other types of supports than a cantilever beam should be considered.

Note: No further development of this type of net-force sensor was undertaken.

AFSWC-TN-57-27   Unclassified Report
Armour Research Foundation   Contract AF 33(616)-2534

THE FEASIBILITY OF GENERATING VARIOUS DESIRED PRESSURE
WAVE FORMS IN SHOCK TUBES THROUGH THE SUCCESSIVE
DETONATION OF EXPLOSIVE CHARGES

This technical note presents an analysis of the relationships among gas flow variables behind an explosive-generated shock front advancing in a constant area channel. A density distribution behind the shock front of the form

$\rho = \rho_S \left(\dfrac{r}{R} \right)^g$ is assumed, where ρ is the gas density at a distance r, from the

explosion source, and ρ_S is the gas density at the shock front distance R, also

measured from the explosion source. The exponent g is determined from physical considerations. Application of the principles of observation of mass, momentum, and energy, together with the assumed density distribution, leads to a particle velocity distribution, a pressure wave form, and a shock strength-scaled distance decay curve. Values of the flow variables at the shock front are, of course, determined by the Rankine-Hugoniot relations.

The analogous flow variable relationships are derived by an approximate method for the case where several explosive charges are detonated successively. By employing this analysis, one may calculate the charge weights, detonation time delays, and explosion source distances required to generate pressure wave forms of various shapes. The calculations are presented for three particular wave forms, including nonpeaked and multiple-peaked cases.

The analysis made in this study shows that, within the validity of the assumptions made, it is possible to generate the desired pressure wave forms. This may be accomplished by detonating a series of charges, of the appropriate sizes, at the proper times. The analysis tells the size of the charges needed and at what time each is to be detonated in order to generate the predetermined wave form. Detailed specifications for the generation of the three desired wave forms are presented in the body of the report.

AFSWC-TN-57-18   Unclassified Report
Armour Research Foundation   Contract AF 33(616)-2534

STUDY OF SHOCK ABSORBENT DEVICES

The theoretical analyses carried out in this study show that it is possible to eliminate the reflections of a plane flat-top blast wave from the partially open end of a shock tube. This is accomplished by placing a grid at the end of the tube. The area ratio is the principal variable which defines the magnitude of the reflected signal, grid geometry and the viscosity being of secondary importance. The analysis predicts the magnitude of the reflected signal when a shock wave is incident upon the grid at the end of the shock tube.

The analysis further illustrates the effectiveness of the grid in both reducing and delaying the reflected signal from the end of a shock tube whenever a peaked shock wave is incident upon it.

The case of a grid within a constant area channel (shock tube) is also treated and the strength of the transmitted and reflected shock waves is presented (for air.) The results are presented as a function of the incident shock strength and the grid area ratio.

Note: The theory has not yet been subjected to tests for practical application. One purpose, of course, would be to allow observation time in the shock tube test section to be increased before the disturbing reflection or rarefaction wave arrives there from the end of the shock tube.

AFSWC-TN-56-66   Secret-RD Report
Armour Research Foundation   Contract AF 33(616)-2534

TEST PLAN FOR PROJECT 3.4 OPERATION PILGRIM (PLUMBBOB)

This report outlines a test plan for Operation Pilgrim Project 3.4 utilizing existing structures in the Nevada Test Site. The test plan includes (1) response of drag-type buildings, (2) tests of concrete panels, (3) airblast effects on underground structures, (4) interior loading and response of underground structures in the precursor region, (5) blast loading on interior obstacles, (6) blast loading behind failing walls, and (7) miscellaneous items. (U)

Note: This operation later became the full-scale atomic test PLUMBBOB.
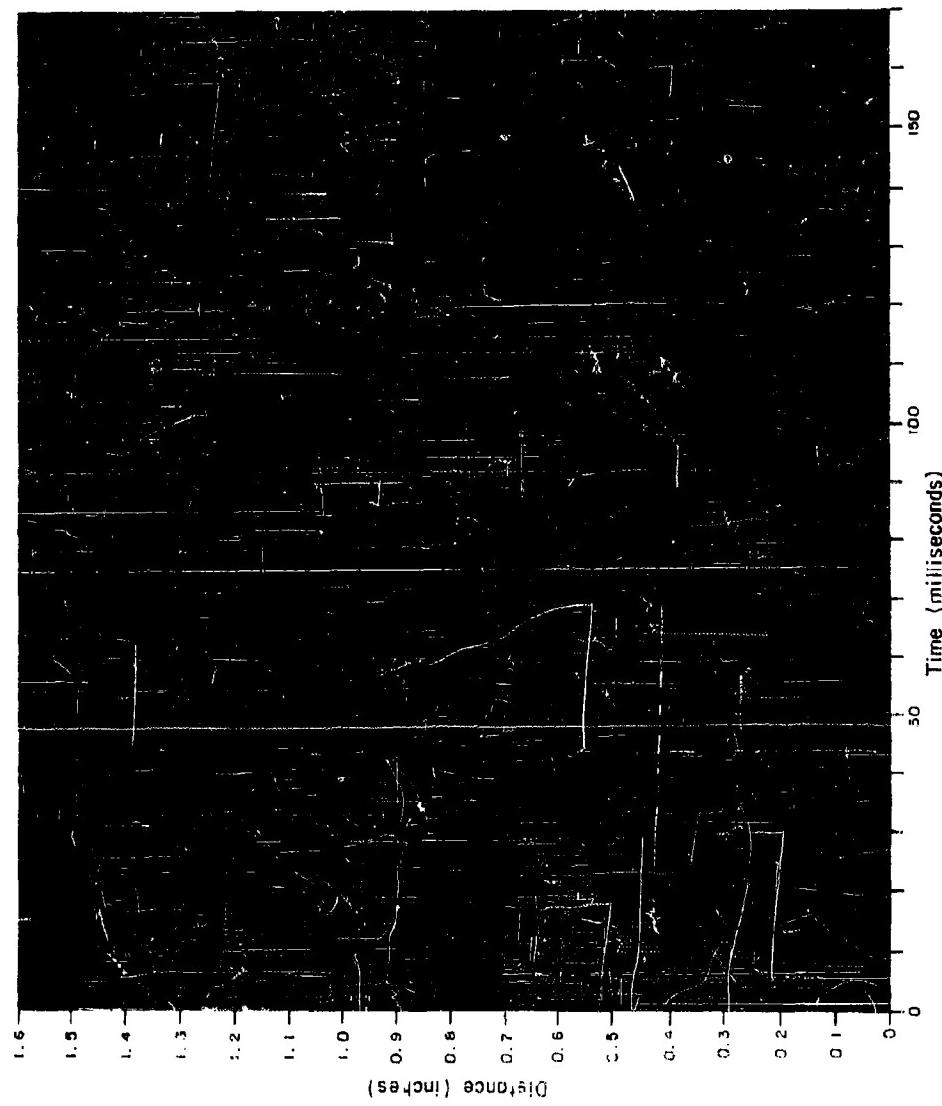
Radiograph of Soil Motion under Shock Load

Enlarged print of the motion of lead pellets buried in a soil sample at the end of a shock tube, when the surface of the soil reflected a 60-psi air shock. The film and an intensifying screen were on a drum camera behind a slit, receiving a 4 ms exposure from a constant-potential X-ray machine, through 5 inches of Ottawa sand. The displacement of 1.5 inches, downward, required approximately 150 ms. Taken by American Machine and Foundry, Mechanics Research Division, under Contract No. AF 29(601)-4154, "Radiographic Instrumentation Study."
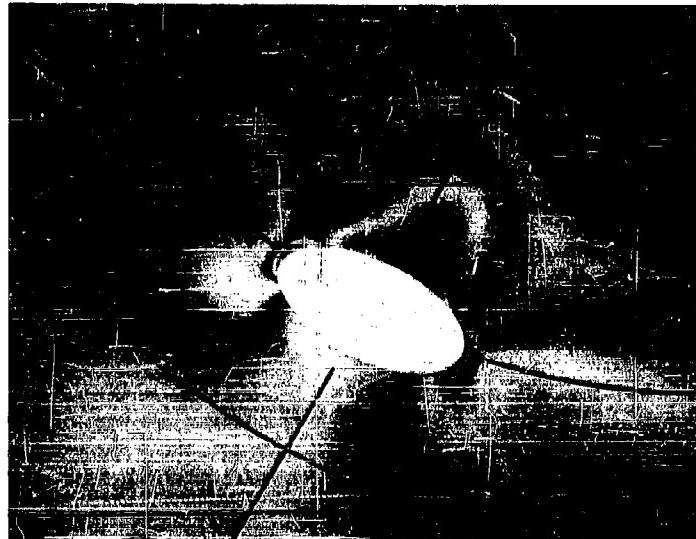
1576 Microseconds After Impact
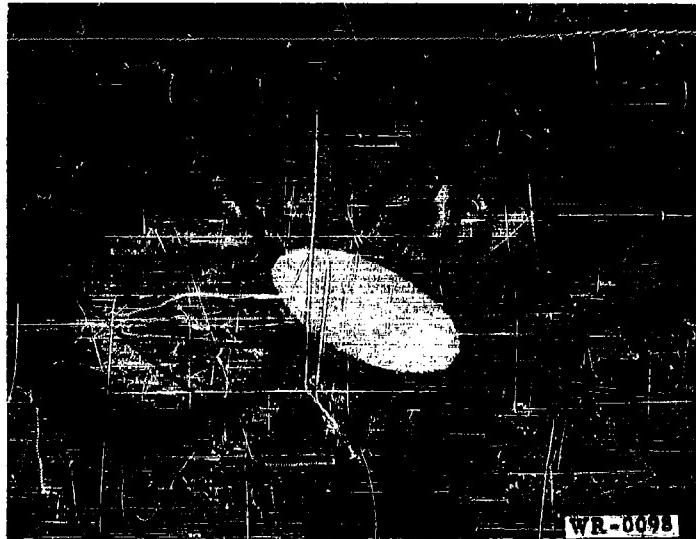
3152 Microseconds After Impact

Microflash photographs showing the fringe order distribution
around the boundary of a hole 1576 microseconds and 3152
microseconds after impact. (Photo from AFSWC TR 61-25
Stress Wave Phenomena in Semi-Solids)

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In-House Report

Proceedings of Third Shock Tube Symposium, 10-12 March 1959

This technical memorandum presents the papers which were delivered at the
third Air Force Special Weapons Center Shock Tube Symposium. The purpose
of this symposium was to exchange information on the development, techniques,
operation, and instrumentation of shock tubes. The papers presented and their
authors are listed below:

(1) Resume of Experiments Conducted in the High-Pressure Shock Tube
of the Gas Dynamics Laboratory at NASA - Jim J. Jones, NASA Langley
Research Center.

(2) A Probe for Determining Flow Conditions in a Short Duration Hyper-
sonic Stream - A. V. Former, Lockheed Aircraft Corporation.

(3) Flow Phenomena in the Convair Free Jet Shock Tunnel - Karl A. Faymon,
Theoretical Aerodynamics Group, Convair.

(4) An Explosive Driven Conical Shock Tube for the Study of Spherical
Shock Waves - William S. Filler, US Naval Ordnance Laboratory.

(5) Kinetics of Hydrogen Recombination in a Chemical Shock Tube - C. V.
Metzler and W. H. Moberly, North American Aviation, Inc., Rocketdyne
Division.

(6) Measurement of O_2 Concentration Behind Shock Waves Using an Ultra-
violet Absorption Technique - John S. Evans and Charles J. Schexnayder, NASA
Langley Research Center.

(7) Diffusion Effects on Shock Structure in a Plasma - O. W. Greenberg
and H. K. Sen, Air Force Cambridge Research Center, and Y. M. Treve,
Block Associates, Inc.

(8) Techniques of Pressure Measurement on an Airfoil in a Shock Tube -
J. Ray Ruetenik.

(9) The Application of Pressure and Force Transducers in Shock Tunnel
Aerodynamic Studies -C. J. Harris and E. M. Kaegi, General Electric, Missile
and Ordnance Systems Department.

(10) Shock Tube Studies of the Effects of Sharp-Rising, Long-Duration
Overpressures on Biological Systems - D. R. Richmond, R. V. Taborelli,
F. Sherping, M. B. Wetherbe, R. T. Sanchez, V. C. Goldizen, and C. S. White,
Lovelace Foundation.

(11) Program for the NCEL Blast Simulator - S. L. Bugg, Navy Civil
Engineering Laboratory.

(12) Factors in the Design of Shock Tube Facilities -D. B. Singer, Armour
Research Foundation.

(13) The Shock Chamber - A Device for Producing High Strength, Spherically Expanding Shock Waves - Kenneth Kaplan and A. B. Willoughby, Broadview Research Corporation.

(14) A One-Inch Force Gage for Drag Measurements in the Shock Tube - William G. Zuke, US Naval Ordnance Laboratory.

(15) Changes in Drag Caused by Shielding - George A. Coulter, Ballistic Research Laboratories.

(16) A Comparison of Pressure Coefficients Obtained in Wind Tunnels to Shock Tube and Field Tests - Captain Marcus L. Whitfield, Armed Forces Special Weapons Projects.

(17) Interaction of Blast Waves with Wings, Part I. Ten-Foot Diameter Free Jet Shock Tube - Harold B. Pierce, NASA Langley Research Center.

(18) Interaction of the Blast Wave with Wings, Part II. Wave-Table Studies- Donald R. McFarland, NASA Langley Research Center.

(19) Experiments and Theory on Explosive Decompression in the Six-Foot Shock Chamber - T. H. Schiffman and A. H. Wiedermann, Armour Research Foundation.

(20) Theory of Filling Process for Chambers; Shock Tube and Field Tests - A. H. Wiedermann, Armour Research Foundation.

(21) Diaphragm Calibration Techniques in a 2.00-inch Diameter Shock Tube - George H. Tweney, Boeing Airplane Company.

SWR-TM-58-3
In-House

Proceedings of Second Shock Tube Symposium (5-6 Mar 58)

This Technical Memorandum presents the papers which were delivered at the second Air Force Special Weapons Center Shock Tube Symposium. The papers presented are listed below:

(1) Shock Tube Wind Tunnel Research at the US Naval Ordnance Laboratory.

(2) Shock Tube Studies of Blast Pressures behind Frangible Wall Panels.

(3) A Comparison of Shock Tube and Field Test Data on the Pressure Buildup behind Frangible Walls.

(4) Some Results of a Shock Tube for Biomedical Investigation.

(5) Experimentation with the General Electric Six-Inch Shock Tunnel.

(6) Pressure Time History in a Chamber Subjected To Shock Wave Filling Through an Orifice.

(7) Determination of the Time History of the Flow Field about Blunt
Bodies in a Shock Tube.

(8) Some Experiments with Periodic Shocks.

(9) On the Effect of Attenuation on Gas Dynamic Measurements Made in
Shock Tubes.

(10) Generation of Pressure Wave Forms through the Detonation of
Explosive Charges.

(11) Problems in the Use of Piezo-Gages for Shock Tube Instrumentation.

(12) Determination of the Dynamic Response Characteristics of Pressure
Measuring Systems Utilizing Shock Tube Testing Techniques.

(13) High Temperature Effects in Shock Structure.

(14) Shock Wave Calculations for High Temperature Gases.

(15) Heat Transfer Measurements on a Hemisphere-Cylinder in the
Lockheed Three-Inch Shock Tube.

(16) A Particular Application of a Conventional Shock Tube for the Study of
Transient Ignition and Combustion in Subsonic Flow.

(17) One-Dimensional Shock Waves from an Axially Symmetric Electrical
Discharge.

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In-House Report

Proceedings of First Shock Tube Symposium (26-27 Feb 57)

This Technical Memorandum presents the papers which were delivered at the
First Air Force Special Weapons Center Shock Tube Symposium. The papers
presented are listed below:

(1) The Air Force Shock Tube as a Research Tool.

(2) Design and Performance of the General Electric Six-Inch Shock
Tunnel Facility.

(3) The Development of a Shock Tube to Generate Variable Stepped Shock
Fronts.

(4) Studies of Transient Air Forces on Two-Dimensional Airfoils.

(5) Studies of Grids in Shock Tubes.

(6) The Development of the Shock Tube Facility for Airfoil Studies.

(7) The Surface Film Thermometer: A Versatile Shock Tube Technique.

(8) Some Observations of Bifurcated Reflected Shock Waves.

(9) Numerical Solution for the Reflection of a Compression Wave from a Rigid Wall.

(10) The Use of the Shock Tube in Hypersonic Research.

(11) Study of Re-entrant Corners.
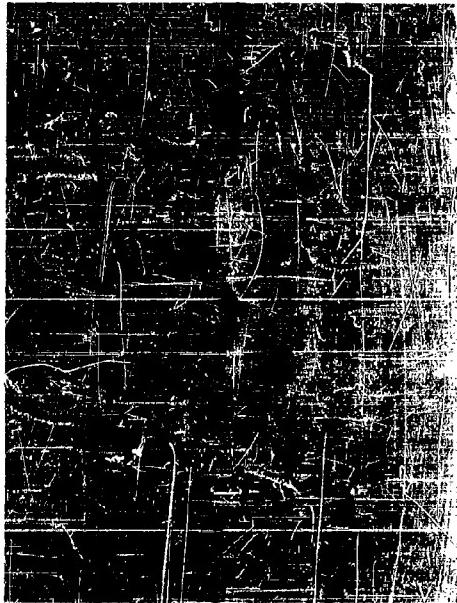
Operation HARDTACK photos of Project 1080's nonresponding-type domes, with a shell thickness of 24 inches, subjected to 70 psi overpressure. Detailed results have been published in DASA Weapon Test Report 1425.

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